CRANFIELD UNIVERSITY

SERGI DORDAL VILÀ

CONTROL SYSTEMS AND ENERGY STORAGE OF LARGE-AREA PHOTOVOLTAIC SYSTEMS AT CRANFIELD UNIVERSITY

SCHOOL OF ENERGY
Renewable Energy Engineering

MSc THESIS
Academic Year: 2016 – 17

Supervisor: Dr Jerry Luo
September 2017

CRANFIELD UNIVERSITY

SCHOOL OF ENERGY
Renewable Energy Engineering

MSc THESIS

Academic Year 2016 - 17

SERGI DORDAL VILÀ

Control systems and energy storage of large-area photovoltaic systems at Cranfield University

Supervisor: Dr Jerry Luo
September 2017

This thesis is submitted in partial fulfilment of the requirements for the degree of MSc Renewable Energy Engineering

ABSTRACT

As solar photovoltaics share is continuously increasing in Europe, the aim of this project is to provide a customer-focused solution to achieve a more sustainable energy supply for Cranfield University by means of a large-area photovoltaics system located in the university land.

PV technology suitable for large-area usage has been identified and evaluated. A complete design of the system has been developed and the performance in terms such as generation, control and energy storage of the PV has been studied. Some existing methodologies have been used for this purpose. Overall costs and benefits of the project have been assessed. A sensitivity analysis has also been realised to identify the key parameters whose variation makes the higher impact to the outcome of the project. Finally, an environmental assessment has been included to focus on the impacts of a PV farm on the site.

Keywords:

Renewable energy, PV farm, dimensioning, power management, costs, environment.

ACKNOWLEDGEMENTS

My sincere gratitude goes to my supervisor Dr Jerry Luo for his guidance during all the stages of my research and also for all the valuable discussions we had during the confection of this thesis.

Also I would like to thank my family and my partner for their inestimable support during the process.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

AC	Alternating Current
AOI	Angle of Incidence
DC	Direct Current
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
GHI	Global Horizontal Irradiance
GPC	Generalised Predictive Control
HSAT	Horizontal single-axis tracker
HTSAT	Horizontal single-axis tracker with tilted modules
IRR	Internal Rate of Return
MPP	Maximum Power Point
MPPT	Maximum Power Point tracking
PID	Proportional Integral Derivative
PV	Photovoltaic
ROI	Return on Investment
TSAT	Tilted single-axis tracker
VSAT	Vertical single-axis tracker

1. INTRODUCTION

1.1 Background

PV systems have had a major boost in recent years due to the increased cost of fossil fuels caused by the progressive exhaustion of the reserves and environmental policies from governments. These factors have led to a higher investment on PV technologies and as a result the costs for such systems have been dropped, making them an attractive option for electricity generation.

Cranfield University is in a privileged situation for its land availability and implementing a large-scale PV farm is a feasible option to enhance their self-sustainability in an environment-friendly manner as well as reducing the costs of its electricity supply.

1.2 Objectives

The aim of this study is to provide the procedure to implement a large-scale PV farm in Cranfield University as well as offering a technical and complete view of the main features and components of a PV system.

Furthermore, different strategies for optimising the system and for the power management will be provided to give the reader a more customer-based coverage.

Finally, this report is intended to be a starting point for exploring other strategies for PV configuration and operation in the future.

1.3 Scope

This report covers in detail the description of the PV system in terms of components, focusing especially in control and storage.

It also comprises the entire dimensioning of the PV farm from empirical data of irradiance conditions and consumption along with selecting the appropriate location for the system.

Then a forecast of the performance of the designed PV farm is provided and analysed to assess the potential outcome of the system.

The costs of the project have also been covered in detail in order to realise a fair estimation of the viability and profitability of investing on this technology its application in Cranfield University. A sensitivity analysis has also been performed to check the robustness of the system and to identify the key parameters affecting the outcome.

Finally an environmental assessment is included to define the impact of the project at the site.

2. IMPLEMENTING A PV FARM IN CRANFIELD UNIVERSITY

2.1 System description

A photovoltaic system or PV system consists of one or more arrays of solar PV panels generating DC electricity. Each panel is controlled by a DC/DC converter to ensure an optimal operation. An inverter transforms the DC electricity to AC prior to be supplied to the loads or to the grid. The excess of energy generated by the PV array can be either fed into the grid or stored in batteries. DC/DC converters can also be used as charge controllers for the battery bank. A schematic of the system is given by Figure 2.1.

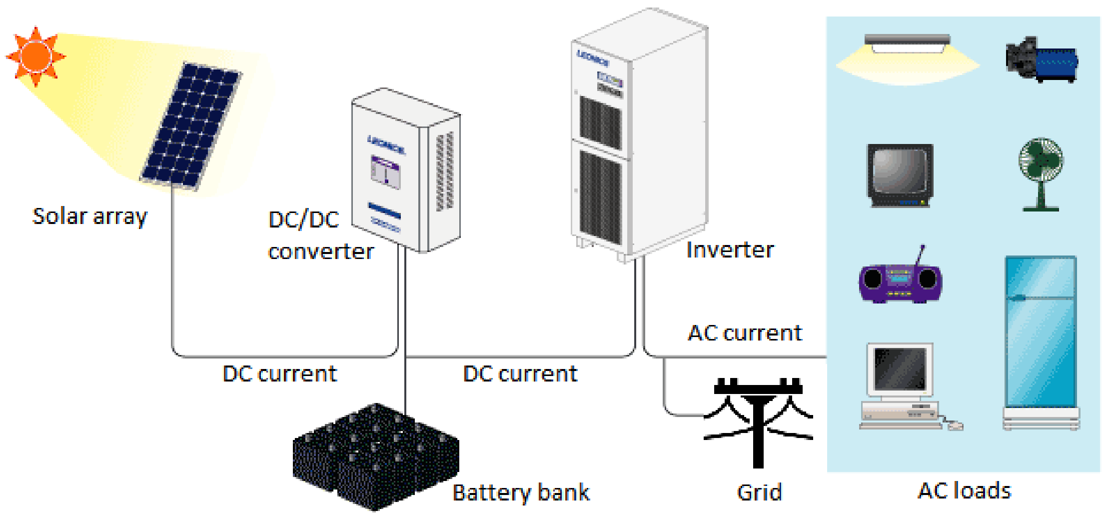

Figure 2.1 Schematic of a PV system.

2.2 Control techniques

The aim of a control system is to optimise the energy production of PV modules. There are basically two strategies to achieve that, one is to maximise the electricity production of the panels by conditioning their electrical output, while the other consists in increasing their available power (irradiance).

Focusing on the first option, power delivered by the PV modules is controlled by the DC/DC converters by a *Maximum Power Point Tracking (MPPT)* strategy. By contrast, the irradiance on the solar cells can be maximised by tracking the sun position.

2.2.1 Maximum Power Point Tracking (MPPT)

The electrical output of PV panels depends mainly on three parameters: irradiance, cell temperature and load characteristics. These determine the voltage, current and power supplied by the cells. PV panel manufacturers typically include a figure of the I-V curves under different irradiance and temperature conditions in their datasheets. The working point is determined by the intersection between the load curve and the I-V curve as illustrated by Figure 2.2.

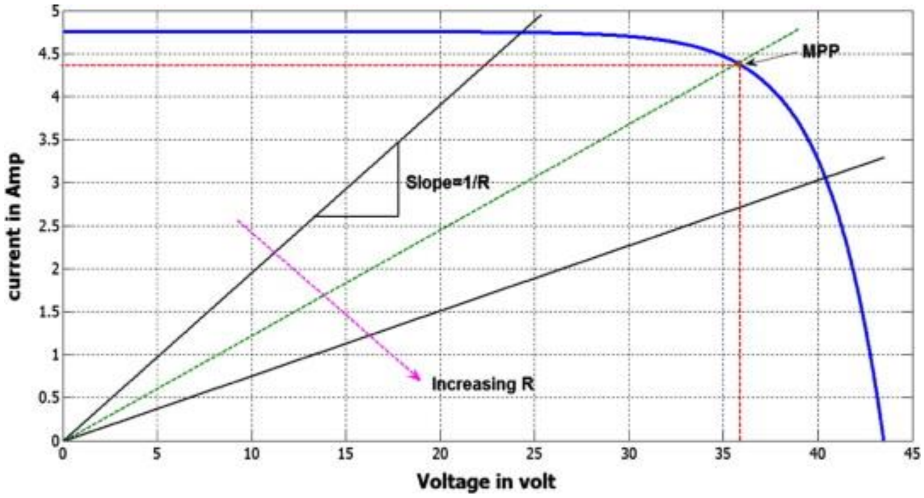

Figure 2.2 I–V curve of PV module and various resistive loads [1].

The *Maximum Power Point* or *MPP* highlighted in Figure 2.2 corresponds to the point of the I-V curve where the power is maximum. This point is constantly changing due to the time-varying characteristics of the irradiance, temperature and load conditions. The purpose of MPPT is to force the PV cells to operate the closest to the MPP as possible.

DC/DC converters act as MPP trackers, operating by changing the DC input current to AC, then running through a transformer, and finally rectifying it back to DC, followed by an output regulation [2]. The equivalent electric circuit can be represented as shown in Figure 2.3, where U_{PV} and I_L are the voltage and current of PV modules, U_O and I_O are the voltage and current supplied by the DC/DC converters and R_L represents the load [3].

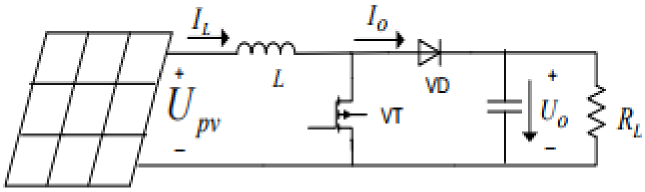

Figure 2.3 Schematic of electric circuit of a PV system.

Converters modulate the output voltage by means of the duty cycle *D* as:

$$U_o = \frac{1}{1-D} U_{PV} \tag{2-1}$$

Then, the circuit can be rearranged by applying Thevenin's theorem as shown in Figure 2.4, where R_{pv} is the resistance of the modules.

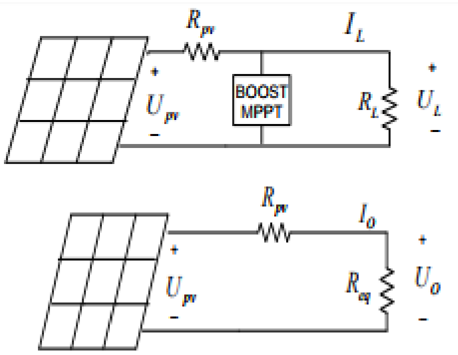

Figure 2.4 Equivalent transformation of the circuit

The equivalent resistance R_{eq} can be expressed by (2-2):

$$R_{eq} = R_L(1-D)^2 \tag{2-2}$$

The strategy of MPPT is to regulate this equivalent resistance adjusting the duty cycle to track the MPP, which is achieved when $R_{eq} = R_{PV}$ as shown in (2-3):

$$P_{max} = \left(\frac{U_{PV}}{R_{pv} + R_{eq}}\right)^2 = \left(\frac{U_{PV}}{2R_{eq}}\right)^2 \tag{2-3}$$

Although other MPPT techniques are also used, currently the main MPPT strategy employed is the *Perturbation and Observation (P&O)* method. The main advantages of this technique are its good performance and simplicity.

The easiest way to employ the P&O method is by means of a PID control, which consists in giving feedback and correcting deviation depending on history error data, however this implies some contradiction between precision and time response.

To overcome the issues of PID control, systems using *Generalised Predictive Control (GPC)* are trending as they have the capability to realise self-adaptive control [3]. Further information regarding P&O MPPT control, can be found on the following publications [3, 4].

2.2.2 Sun-tracking

Electricity generation can be also increased by facing the array towards the sun position, as the area receiving direct irradiance is larger. However, the land required per module increases as well, since panels' rotation implies a greater shadow variation throughout the day, and arrays must be placed further from one another to avoid shading.

The most common sun-tracking strategies are three: 1-axis tracking, 2-axis tracking and seasonal changing of the tilt angle of a fixed-tilt array.

The last mentioned is the simplest, and consists in adjusting the tilt of the panels (commonly 2 or 4 times a year) to compensate the variation of sun's elevation throughout the year. This measure can add up to 5% of power generation compared to a not-adjusted tilt [5]. Nevertheless, it requires and additional racking system for the array that would slightly raise the cost of the system.

1-axis tracking systems are designed to follow the path of the sun rotating during the day from east to west. To achieve that, there are plenty of strategies and technologies, but they can be divided in three main groups according to their axis of rotation: *horizontal single-axis trackers (HSAT)*, *vertical single-axis trackers (VSAT)* and *tilted single-axis trackers (TSAT)*.

HSATs' axis of rotation is parallel to the horizontal plane and is usually aligned from north to south. This tracking strategy is the most efficient in terms of land usage as panels can be distributed in rows sharing the same axis, as shown in

Figure 2.5. HSAT systems perform at their best at low latitudes, as the panels are usually parallel to their rotation axis (tilt angle is 0º at solar noon) [6]. *Horizontal single-axis trackers with tilted modules (HTSAT)* can be used to increase power generation of the modules, but they require more area to avoid shading.

Figure 2.5 Horizontal single-axis tracking system [7].

In VSAT systems, panels rotate at a constant tilt with a rotation axis perpendicular to the ground. As illustrated by Figure 2.6, VSAT require more area than HSAT as they cannot be distributed in rows, and layout optimisation becomes more challenging. However, these systems are more suitable at high latitudes than HSAT [6].

Figure 2.6 Vertical single-axis tracking system [8].

TSAT systems have a rotation axis in the range between 0º to 90º. They are a midterm between HSAT and VSAT, having a combination of the benefits and drawbacks of each strategy. An example of such systems is given by Figure 2.7.

Figure 2.7 Tilted single-axis tracker system [9].

In terms of power generation, 1-axis tracking systems can produce up to a 30% more energy than fixed-tilt systems [5, 10, 11]. Their contribution is less noticeable for high latitudes and during winter. However, tracking implies a higher cost than fixed-tilt in terms of capex and operating and maintenance (O&M), and has a negative impact in the overall reliability of the system due to the presence of moving parts.

Finally, 2-axis tracking systems are able to follow the exact sun position as they have 2 degrees of freedom. An example of such systems is represented in Figure 2.8. Their tracking precision can make a boost in generation up to a 40% more than fixed-tilt systems [5, 10, 11]. As 1-axis systems, their contribution is maximum in summer and at low latitudes. Nevertheless, components and algorithms for 2-axis tracking are sensibly higher than 1-axis, resulting in a higher cost and also decreasing the reliability of the system.

Figure 2.8 Dual-axis tracking system [12].

Tracking has been cost-effective for many years due to the cost of PV panels, but current market prices for the modules are sensibly lower than just a few years ago, and now tracking might not be the optimal choice for some projects [5]. Furthermore, trend for panel cost is to continue decreasing in the next years but at a slower rate [13]. Comparing 1-axis vs 2-axis tracking, the first is more optimal because the lack of generation is small compared to the higher system costs for 2-axis.

Then, for implementing a PV farm in Cranfield University the two main options are fixed-tilt modules or 1-axis tracked. Depending on when the power is needed the most, winter or summer, the best choice might be different. For the same total power generated in a year, if we compare a PV farm with 1-axis tracking and another with more fixed-tilt modules, the first option provides more power in the summer while the second generates more in the winter.

For this study the main purpose is to minimize the grid supply in winter, and therefore a fixed-tilt system has been selected. Moreover, since Cranfield is located at 52º latitude, tracking would produce less generation surplus than in southern areas in Europe.

2.3 Dimensioning

Once the choice of using fixed-tilt arrays is made, the following steps are selecting the type of panels that will be used and defining the appropriate tilt angle for them. Then, the system must be dimensioned for supplying the required power to the load under estimated weather and irradiance conditions.

2.3.1 Panel selection and tilt-angle

The criteria used for selecting the PV panel type has been to maximize the rated power generated per unit area, as an attempt to optimise the land usage for the PV farm. According to panel comparators (see *Appendix* PV panel comparison*A.1 PV panel comparison*), the panel satisfying this criteria is the SunPower 315. This module comprises 96 monocrystalline cells and produces 315W_p with a conversion efficiency of 19.3% at standard conditions (irradiance of 1000W/m^2, Air mass of 1.5 and cell temperature 25ºC). Datasheet is available at [14].

For selecting the optimum tilt angle, this has been considered to be constant throughout the year, thus seasonal adjusting will not be applied. In many systems, especially for residential applications, the tilt is selected equal to the latitude, but this is a rough approximation. Some research has been done about tilt angle selection and more sophisticated models have been developed [15]. For this application the tilt angle has been calculated following the regression models in (2-4) provided by [16]. These models were built accounting for each configuration of latitude and season, calculating insolation at the panels for several times during the day. Then an iterative method is used to determine the angles that give the maximum total insolation during each season and for the year. From these values a linear formula can be used to determine the optimal angle depending on the latitude:

$$\theta_T = 0.76\lambda + 3.1^{\text{o}} \tag{2-4}$$

where θ_T is the tilt angle of the panels in degrees and λ is the latitude.

Since Cranfield latitude is 52º, the **optimal tilt angle** for the PV panels is[1] **42.6º**. In terms of orientation, panels should be placed facing south.

2.3.2 Sun position

Sun position relative to a fixed point in Earth's surface is a key parameter to determine the performance of a PV system. As illustrated by Figure 2.9, sun position can be characterised by azimuth angle, related to cardinal coordinates, and either elevation or zenith angles, which are complementary.

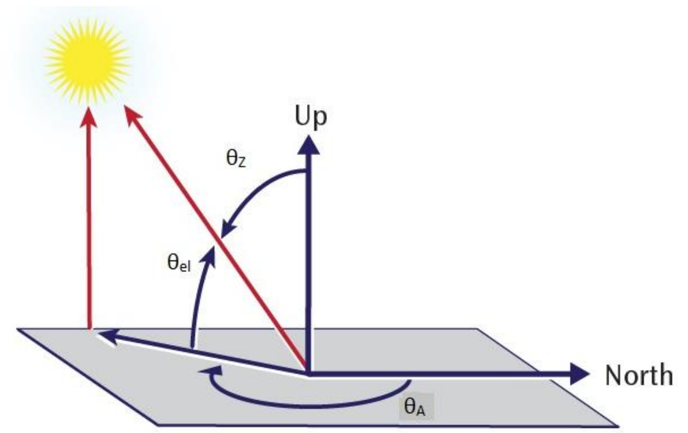

Figure 2.9 Solar angles from a surface viewpoint [17].

Determining those angles involve a series of calculations based on approximate values, therefore a certain error is inevitable. For sake of simplicity, the basic solar position model [18] is employed. A more sophisticated model can be found in [19]. The basic model is based on the following key parameters: *declination of the sun*, *hour angle*, *local time* and *solar time*.

Declination of the sun is defined as the angle between Earth's axis of rotation and the plane perpendicular to the line connecting the centres of Earth and sun, represented as θ_d in Figure 2.10. This angle is only zero at the spring and autumn

[1] Some accuracy may be lost as the formula is optimised for latitudes between 25º and 50º.

equinoxes, and by convention it is defined positive during summer and negative during winter, and oscillates between $\pm 23.45^{\circ}$.

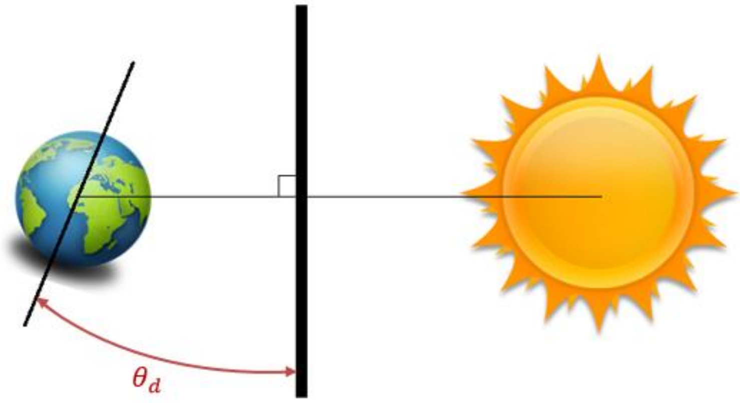

Figure 2.10 Declination of the sun.

The mathematical approximation for the declination is given by (2-5).

$$\theta_d = \frac{23.45\pi}{180} \sin\left(2\pi \frac{284 + n}{365}\right) \quad (2\text{-}5)$$

where θ_d is the declination angle in radians and n is the day of the year.

Focusing on hour angle, this is the angle describing the apparent daily orbit of the sun from a fixed point of view in earth surface. It is strictly a conversion of the solar time (2-6), it varies from 180º to -180º during the day and by convention it is defined as 0º during solar noon (when the sun reaches the maximum elevation).

$$\theta_{hr} = \pi \frac{12 - T_{solar}}{12} \quad (2\text{-}6)$$

where θ_{hr} is the hour angle in radians and T_{solar} is the solar time in hours.

Similarly than the hour angle, solar time is defined as the relative position of the sun to and observation point, this magnitude is important as while local time is fixed for every time zone, variations in longitude across the same zone implies different solar times for each location. Equation (2-7) gives the expression of solar time as a function of local time and other parameters.

$$T_{solar} = T_{local} + \frac{Eq_t}{60} + \frac{Long_{sm} - Long_{local}}{15} \quad (2\text{-}7)$$

where T_{solar} is the solar time in hours, T_{local} is the local time in hours, $Long_{sm}$ is the longitude of the standard meridian in degrees, $Long_{local}$ is the longitude of the observer in degrees and Eq_t is the equation of time in minutes.

In (2-7), the 15 corresponds to the escalation from degrees to hours (360º/24h). For Cranfield University $Long_{sm} = 0^{o}$ and $Long_{local} = -0.63^{o}$. The equation of time (2-8) is a set of approximations to correct the difference between solar and local time depending on the day of the year.

$$1 \leq n \leq 106 \longrightarrow Eq_t = -14.2\, sin\left(\frac{\pi(n+7)}{111}\right) \quad (2\text{-}8)$$

$$107 \leq n \leq 166 \longrightarrow Eq_t = 4.0\, sin\left(\frac{\pi(n-106)}{59}\right)$$

$$167 \leq n \leq 246 \longrightarrow Eq_t = -6.5\, sin\left(\frac{\pi(n-166)}{80}\right)$$

$$247 \leq n \leq 365 \longrightarrow Eq_t = 16.4\, sin\left(\frac{\pi(n-247)}{113}\right)$$

where Eq_t is the equation of time in minutes and n is the day of the year.

From declination and hour angles, sun zenith (2-9) and azimuth (2-10) angles for a certain latitude can be calculated as:

$$\theta_Z = cos^{-1}(sin\lambda\, sin\theta_d + cos\lambda\, cos\theta_d\, cos\theta_{hr}) \quad (2\text{-}9)$$

where θ_Z is the zenith angle, θ_d is the declination, θ_{hr} is the hour angle and λ is the latitude.

$$\theta_{hr} \leq 0 \;\longrightarrow\; \theta_A = \theta_{A1} = cos^{-1}\left(\frac{sin\theta_d\, cos\lambda - cos\theta_d\, sin\lambda\, cos\theta_{hr}}{sin\,\theta_Z}\right) \quad (2\text{-}10)$$

$$\theta_{hr} > 0 \;\longrightarrow\; \theta_A = \theta_{A2} = 2\pi - \theta_{A1}$$

where θ_A is the azimuth angle in radians.

A useful Matlab script file for calculating all solar angles hourly for all year is provided in *Appendix B.1 Matlab script for calculating solar angles and AOI.*

2.3.3 Irradiance estimation

Irradiance is the amount of solar radiation per area. When extra-terrestrial insolation reaches the Earth, due to the effects of terrestrial atmosphere, radiation is diffracted, absorbed and reflected at a certain degree. Typically irradiance incident on a surface is characterised in three different magnitudes.

The total component falling on a horizontal surface is known as *global horizontal irradiance (GHI)*. GHI can be measured directly by a pyranometer.

Direct normal irradiance (DNI) corresponds to the irradiance provided directly by sun beams. It can also be measured by instruments such as cavity radiometers and pyrheliometers. Some models have also been developed to estimate DNI from GHI measurements [20, 21].

Diffuse horizontal irradiance (DHI) is the amount of irradiance on a horizontal surface that has been diffused by the atmosphere.

GHI can be expressed as a combination of DNI and DHI as:

$$GHI = DHI + DNI\ cos\theta_Z \qquad (2\text{-}11)$$

where θ_Z is the sun zenith.

For this project, hourly data (averaged per month) of GHI, DNI and DHI have been obtained from the PVGIS European Communities database for years 2001-12 [22].

For a PV array, though, it is mandatory to determine the *plane of array irradiance*, since this is the amount received by the cells to generate electricity. It can be obtained by (2-12):

$$E_{POA} = E_b + E_g + E_d \qquad (2\text{-}12)$$

where E_{POA} is the plane of array irradiance, E_b is the beam contribution, E_g is the ground-reflected contribution and E_d is the sky-diffuse component.

The beam component can be obtained from DNI as:

$$E_b = DNI\cos(AOI) \tag{2-13}$$

where AOI is the angle of incidence.

The AOI is defined as the angle between the sun beam direction and the vector normal to the plane of the array, therefore the beam component is maximum when the sun is perpendicular to the plane of the array. The expression for AOI is given by (2-14). A Matlab script file for calculating hourly AOI for all year is provided in *Appendix B.1 Matlab script for calculating solar angles and AOI.*

$$AOI = cos^{-1}\left(cos\theta_Z\, cos\theta_T + sin\theta_Z\, sin\theta_T\, cos(\theta_A - \theta_{A,array}\right) \tag{2-14}$$

where θ_Z is the sun zenith, θ_A is the sun azimuth, θ_T is the tilt of the array and $\theta_{A,array}$ is the azimuth of the array[2].

Ground-reflected irradiance depends on the reflectivity of the ground (commonly known as albedo), the tilt of the array and GHI as shown in (2-15):

$$E_g = GHI \cdot albedo \cdot \frac{1 - cos\theta_T}{2} \tag{2-15}$$

Albedo varies from 0 to 1 (0.04 for asphalt, 0.25 for grass, 0.8 for snow…). The contribution of ground-reflected irradiance usually is small, but can be significant in climates where snow is abundant.

For sake of simplicity, for this project sky-diffuse irradiance has been calculated using the isotropic model [23, 24], which assumes that diffuse radiation is uniform across the sky.

$$E_d = DHI\ \frac{1 + \cos\theta_T}{2} \tag{2-16}$$

where θ_T is the tilt of the array.

This component is really important in cloudy days, when it can represent up to 100% of POA irradiance.

---

[2] By convention azimuth is 0º when direction is North, thus $\theta_{A,array}$ is 180º, as panels are facing South.

2.3.4 Consumption estimation

As implementing a PV farm has the aim of supplying part of the electricity required by the university, for dimensioning the consumption, the load has been defined as a middle size office. The average electricity consumed by these buildings is provided by the available database of the *Office of Energy Efficiency & Renewable Energy (EERE)* of the *U. S. Department of Energy* [25]. To approximate the consumption of a Cranfield University building, data corresponding to a middle sized office in Worcester, MA have been used. With these considerations, the **total consumption** forecast is **898,445kWh/year**, hence the PV farm must be dimensioned to produce this amount of energy.

2.3.5 Generation requirements

Due to the variability of PV generation during the year, there are many possible strategies for dimensioning the system. One of them is trying to provide 100% of the energy required by the load from PV during the whole year, avoiding the use of the grid, but this would require a huge amount of panels and batteries for supplying enough power during winter, while for the rest of the year the PV farm would be extremely over dimensioned for a system connected to the grid.

Therefore, for this study the strategy adopted has been to provide approximately the total annual amount of electricity demanded by the office, but relying on the grid during the winter when PV generation is not enough and using the surplus in summer to supply other offices in the university.

Power generated by PV panels in the day of the year *n* at the hour *t* can be expressed as:

$$P_{DC}(t,n) = E_{POA}(t,n) \cdot N \cdot A_p \cdot \eta_p \tag{2-17}$$

where $E_{POA}(t,n)$ is the plane of array irradiance, N is the number of PV panels, A_p is the area of the panels and η_p is the efficiency of the panels.

Then, total energy generated in kWh/year can be calculated as:

$$E_{DC} = \sum_{t=1}^{24} \sum_{n=1}^{365} P_{DC}(t, n) \tag{2-18}$$

To supply the required AC power, PV panels must generate a greater DC amount to compensate for the losses in conversion and storage. Accounting for an **89% efficiency** for a full cycle (see section *3.1 Generation*), total PV generation must be around 1,010,000 kWh/year. Then, rearranging expression (2-17) as:

$$N = \frac{P_{DC}(t, n)}{E_{POA}(t, n) \cdot A_p \cdot \eta_p}$$

For $A_p = 1.63m^2$ and $\eta_p = 19.3\%$, the required number of panels can be obtained iterating for values of *N* and imposing $\sum_{t=1}^{24} \sum_{n=1}^{365} P_{DC}(t, n) = 1{,}010{,}000\ kWh/y$, obtaining $N = 2223\ panels$. For optimizing land usage for the PV farm (*see section 2.4.3 Farm Layout*) finally the **number of panels** selected has been rounded up to **2256**, resulting in a **total DC generation** forecast of **1,025,738 kWh/year**.

Finally, the **rated power** of the PV farm is:

$$P_{N,DC} = N \cdot P_{Np} = 2256 \cdot 315W_P = \mathbf{710.64\ kW_P} \tag{2-19}$$

2.3.6 Storage requirements

Storage is a key parameter for the autonomy of the system, but it is also one of the critical concepts in the cost of the project. Thus, selecting the appropriate storage is crucial. PV applications usually employ batteries, as they commonly operate in DC and for their efficiency, although they are more expensive than other technologies such as thermal storage.

Similarly than for generation, different strategies can be employed to select the storage capacity required by the PV farm. To be coherent with the strategy for dimensioning the generation, the battery bank has been sized to store and supply all the energy demanded by the load during hours with lack of generation, from

March to September. This means that the system can practically[3] operate off-grid during 7 months. The required storage capacity can be determined as the maximum among each month's deficits of energy during night and low sun hours. Mathematically it can be written as:

$$C_{req} = MAX\left(\sum_{t=1}^{24} P_{cons}(m=3,t) - P_{gen}(m=3,t)\,;\sum_{t=1}^{24} P_{cons}(m=4,t) - P_{gen}(m=4,t)\,;\ \dots;\sum_{t=1}^{24} P_{cons}(m=9,t) - P_{gen}(m=9,t)\right) \tag{2-20}$$

$$P_{cons}(m,t) > P_{gen}(m,t)$$

where C_{req} is the required storage capacity in kWh, $P_{cons}(m,t)$ is the power consumption in kW at month m and hour t , and $P_{gen}(m,t)$ is the power generation in kW at month m and hour t.

From Table 3.4 in section *3.3 Energy surplus and deficit*, the maximum deficit in (2-20) is 892kWh, corresponding to a day of March between $1h < t < 8h$ and $17h < t < 24h$.

Further from the total energy, batteries also must be able to provide the required power at these times:

$$P_{r,bat} = MAX\left(P_{cons}(m=3,t) - P_{gen}(m=3,t);\ P_{cons}(m=4,t) - P_{gen}(m=4,t);\ \dots;\ P_{cons}(m=9,t) - P_{gen}(m=9,t)\right) \tag{2-21}$$

$$P_{cons}(m,t) > P_{gen}(m,t)$$

where $P_{r,bat}$ is the required rated power of the batteries in kW, $P_{cons}(m,t)$ is the power consumption in kW at month m and hour t , and $P_{gen}(m,t)$ is the power generation in kW at month m and hour t.

---

[3] For days with less generation than month's average, grid must supply the difference. However, in colder months, for certain days with much generation the grid will not be required.

From Table 3.4 in *3.3 Energy surplus and deficit*, the maximum power deficit in (2-21) is 133kW, corresponding to a day of March at $t = 6h$.

Once the requirements are set, the next step is to decide what type of battery should be used. The main choice is between two families: lead-acid or lithium-ion. Lead-acid batteries are a mature technology used for some decades in PV applications, while lithium-ion is a more recent technology used initially for car batteries, but since 2016 it is also starting to be used for large-scale PV farms.

Comparing the two options in terms of cost, lead-acid batteries typically oscillate between 100-200 per kWh, while lithium-ion are much more expensive, actually above 500$ per kWh [26]. However, focusing of performance, lithium-ion batteries are clearly superior in three key aspects: compactness, resilience and lifecycle, resulting into a more cost effective option [27].

For the Cranfield University PV farm, Tesla Powerpack 2.0 lithium-ion battery + inverter will be used. Each Powerpack has a capacity 210kWh and a rated power of 50kW. For complete characteristics see *Appendix A.2Tesla Powerpack 2.0 Datasheet*.

Finally, considering a **project lifecycle of 20 years**, assuming the batteries **degrade at 0.5%/year** the number of Powerpacks required can be calculated as:

$$N = \frac{C_{req}}{C_N(1 - degradation)} = \frac{892kWh}{210kWh(1 - 0.005 \cdot 20)} = 4.72 \rightarrow 5 \qquad (2\text{-}22)$$

With **5 Powerpacks**, **total storage capacity** of the batteries will be:

$$C_{tot} = N \cdot C_N = 5 \cdot 210kWh = \mathbf{1050}\boldsymbol{kWh} \qquad (2\text{-}23)$$

Then it must be ensured they will supply the required power, and effectively it is, as shown in (2-24) :

$$P_{N,bat} = N \cdot P_N = 5 \cdot 50kW = 250kW > 133kW \qquad (2\text{-}24)$$

2.4 Farm Configuration

Once dimensioning is completed, the final step is to plan the location and configuration of the PV farm.

An optimal row spacing and layout are crucial to maximise land usage and to avoid shading of near external elements or between the panels themselves.

2.4.1 Location

For implementing the PV farm a currently non-used land has been searched to avoid additional costs of land acquisition or decommissioning of existing facilities and with enough space to contain approximately 2200 panels disposed in several rows appropriately separated.

As highlighted in Figure 2.11, a site surrounded by the Technology Park, Martell House, Stilliters Farm and the airport has been selected for its potential.

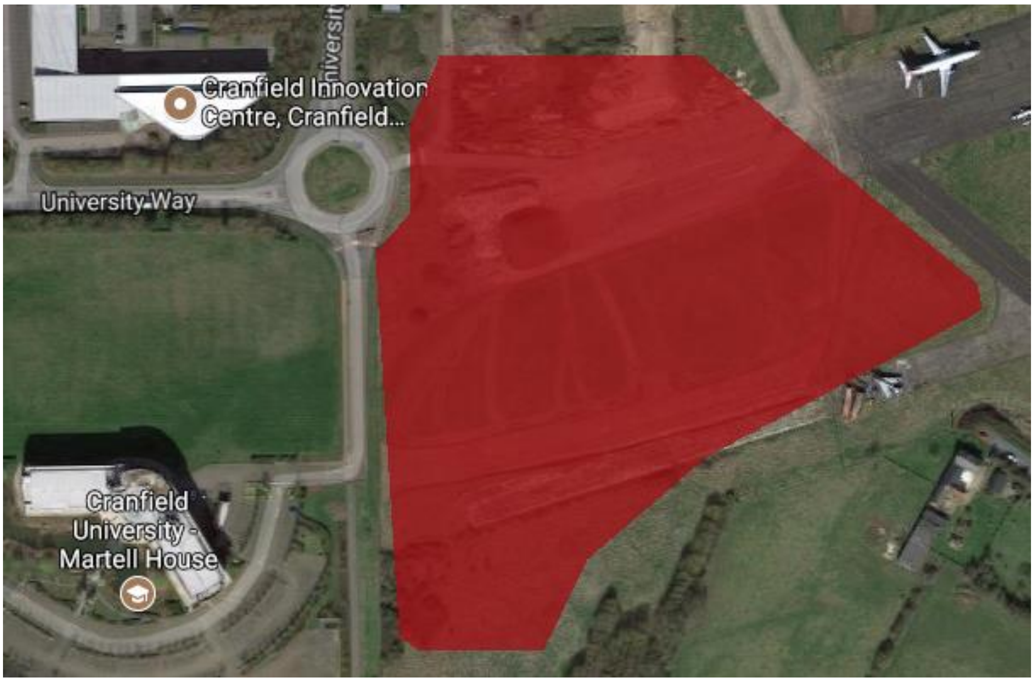

Figure 2.11 PV Array Location, satellite view (by Google Maps).

2.4.2 Shading

Shading is a crucial aspect to consider when designing a PV farm, as if it is underestimated, generation may decrease drastically when the sun elevation is low, such as winter or in hours close to the sunrise and sunset during the rest of the year.

Panels must be placed in a configuration that minimizes the shading caused by other panels. Since no tracking is employed, panels can be placed in multiple rows in the East-West direction. Rows must be inter-spaced considering the sun elevation as illustrated by Figure 2.12.

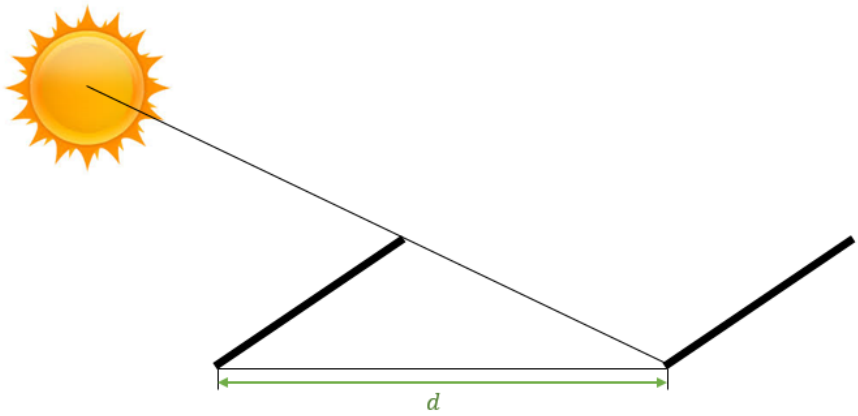

Figure 2.12 Required row spacing

A simple[4] mathematical expression for d is given by (2-25):

$$d = H\ cos\theta_T + H\ sin\theta_T\ tan\theta_Z \tag{2-25}$$

where H is the height of the panels, θ_T is the tilt angle of the panels and θ_Z is the sun zenith.

The first term in (2-25) accounts for the horizontal space occupied by the modules, while the second represents the land separation until next row. Note that this second term is dependent on the sun position, then there is some flexibility for selecting the distance between rows. In this study, a worst case scenario has been considered, the aim is to have **zero overshadowing in December from 10am to 2pm**, when the maximum sun zenith (corresponding to the minimum elevation) is approximately 80.4º. For $H = 1.559m$ and $\theta_T = 42.6^{\text{o}}$, the **required distance between rows is 7.37m**.

[4] Note that the apparent distance between each row depends also on the azimuth angle of the sun. Here this hasn't been considered because it will be dimensioned for a worst-case scenario.

Besides, shadows from objects close to the PV farm must be considered. Potential causes of shading for PV modules are Martell House, Stilliters Farm and the trees. Distance from these obstacles has also been calculated for suffering zero shadowing in December from 10am to 2pm, according to the formula (2-26). Results are given in Table 2.1.

$$d = H\ tan\theta_Z \tag{2-26}$$

where H is the height of the obstacle and θ_Z is the sun zenith.

Table 2.1 Shading data from 10am to 2pm, December, for obstacles close to the PV farm

Obstacle	*H (m)*	*d_{10am} (m)*	*d_{11am} (m)*	*d_{12am} (m)*	*d_{1pm} (m)*	*d_{2pm} (m)*
Trees	6	34m, -28º	26m, -14º	22m, 0º	26m, 14º	34m, 28º
Stilliters Farm	10	57m, -28º	43m, -14º	37m, 0º	43m, 14º	57m, 28º
Martell House	15	85m, -28º	65m, -14º	56m, 0º	65m, 14º	85m, 28º

2.4.3 Farm Layout

After shading characterisation is completed, finally the layout of the PV farm can be set. From calculations in (2-17) in *section 2.3.5*, the required number of panels is around 2220. For optimizing the land usage, rows are designed to have the maximum width in the east-west direction. Each row is numbered from North to South. The description for each row is given in Table 2.2.

Therefore, the **total number of panels is 2256**, requiring a **total area** around **23300m^2 or 2.33hA**. The occupied area is highlighted in Figure 2.13.

Table 2.2 Number of panels per row

Raw nº	*Panels in row*	*Raw nº*	*Panels in row*
1	*115*	***11***	*123*
2	*122*	***12***	*106*
3	*129*	***13***	*102*
4	*136*	***14***	*98*
5	*143*	***15***	*94*
6	*149*	***16***	*90*
7	*155*	***17***	*62*
8	*161*	***18***	*59*
9	*158*	***19***	*56*
10	*145*	***20***	*53*
		TOTAL	***2256***

Figure 2.13 PV farm total area, satellite view (by Google maps)

3. FARM PERFORMANCE

This section is focused on the operation of the PV farm. Here generation and consumption are analysed in detail and the electricity management is described.

3.1 Generation

As mentioned in section *2.3.5 Generation requirements,* the PV system has a total installed power of 710.64kW$_p$ and generates electricity following the expression:

$$P_{DC}(t,n) = E_{POA}(t,n) \cdot N \cdot A_p \cdot \eta_p$$

where $E_{POA}(t,n)$ is the plane of array irradiance at hour t in day of the year n, N is the number of PV panels, A_p is the area of the panels and η_p is the efficiency of the panels.

By means of hourly data of the POA irradiance calculated following the procedure given in section *2.3.3 Irradiance estimation*, hourly DC generation data can be obtained for each day of the year. For ease of analysis, these day-varying data have been averaged to each month and is provided by Table 3.1.

As data show, there is a huge difference in generation between summer and winter, for example electricity production in May, June and July exceeds December and January by more than a 400%. This is the result of having about double of sun hours and vastly more irradiance in those hours.

The system produces about 1GWh a year, and 72% of this amount is generated just in the 6 warmer months (April-September), while in the other half of the year only a 28% is produced.

Comparing the maximum power delivered with the installed power, at noon the PV farm operates at approximately 65% of its potential on average during the summer, while performs just at about 27% in winter. The overall yield is given by (3-1):

$$Y = \frac{E_{DC}}{P_N} = \frac{1{,}025{,}738 kWh/year}{710.64 kW_P} = \frac{1443 kWh}{kW_P \cdot year} \tag{3-1}$$

Table 3.1 PV power generation (DC) in kWh

t (h)	January	February	March	April	May	June	July	August	September	October	November	December	Total year
1	0	0	0	0	0	0	0	0	0	0	0	0	
2	0	0	0	0	0	0	0	0	0	0	0	0	
3	0	0	0	0	0	0	0	0	0	0	0	0	
4	0	0	0	0	0	33.4	28.1	0	0	0	0	0	
5	0	0	0	0	44.7	70.8	60.7	35.2	0	0	0	0	
6	0	0	0	63.8	104.0	129.0	117.0	75.9	40.4	0	0	0	
7	0	0	75.2	156.1	191.7	212.7	201.5	159.4	109.7	49.9	0	0	
8	36.5	67.3	168.5	254.7	281.7	295.4	286.2	246.7	207.4	120.6	56.1	0	
9	79.7	142.8	257.4	341.6	361.8	367.0	360.8	323.9	295.3	206.7	118.9	72.4	
10	138.9	206.1	327.6	407.8	423.2	420.8	418.0	383.1	362.6	272.7	186.5	131.2	
11	177.8	247.9	372.7	448.6	461.1	454.0	454.1	420.6	404.0	312.5	227.4	167.9	
12	191.9	263.5	389.2	461.5	472.4	464.7	466.9	433.3	416.5	323.6	239.2	179.5	
13	179.4	251.9	376.3	446.8	457.8	453.0	455.8	421.4	400.0	305.1	221.5	166.1	
14	141.6	213.0	334.2	404.4	417.1	409.4	421.1	384.6	355.3	259.4	176.5	128.2	
15	82.2	150.6	265.7	337.1	353.8	352.3	365.0	325.9	285.8	190.6	108.6	69.6	
16	26.2	72.6	176.6	249.8	273.0	279.5	290.8	248.9	197.5	106.7	42.0	15.9	
17	0	24.5	80.3	151.8	183.6	199.4	205.9	161.4	102.2	33.9	0	0	
18	0	0	25.6	61.2	98.2	123.6	120.4	77.3	31.5	0	0	0	
19	0	0	0	26.6	44.7	70.8	60.7	28.8	0	0	0	0	
20	0	0	0	0	12.7	27.3	22.0	0	0	0	0	0	
21	0	0	0	0	0	0	0	0	0	0	0	0	
22	0	0	0	0	0	0	0	0	0	0	0	0	
23	0	0	0	0	0	0	0	0	0	0	0	0	
24	0	0	0	0	0	0	0	0	0	0	0	0	
Total day	1054.3	1640.3	2849.5	3811.8	4181.5	4362.9	4334.9	3726.2	3208.2	2181.7	1376.6	930.8	
Total month	32683.9	45929.3	88333.2	114353.5	129626.2	130886.6	134382.5	115512.9	96245.8	67632.7	41297.1	28853.8	**1,025,738**

This power, however, cannot be directly used for the consumption as it has to be converted to AC first. During this process, a fraction of the energy is lost mainly in the inverter, but also in the batteries and converters. For this system this represents approximately and 11% of the total DC power generated, therefore the overall **efficiency** in the electricity conversion since its production until its consumption is **89%** (see *Appendix A.2 Tesla Powerpack 2.0 Datasheet*).

3.2 Consumption

In this section detailed hourly data of the consumption are provided and analysed. As mentioned in section *2.3.4 Consumption estimation,* the load to be fed is a middle sized office consuming close to 900,000kWh a year. Similarly than for generation, data values are presented in Table 3.2 as a month average to be more comparable.

Contrarily than for generation, consumption is greater in winter than in summer by more than 60% and up to 83% in January compared September. It is essentially due to the need of electrical heating[5] and also to higher lightning requirements. Note that the minimum consumption occurs in late spring and early autumn (April, May and September), instead of summer. This is due to the extra power consumed in summer for cooling.

Another big difference between winter and summer is the time when electricity is used. In winter the maximum consumption occur from 7am to 9am in a clear peak demand, corresponding to the time when heating requirements are maximum to increase the base temperature from the night to daily temperature, as the staff come to the office. By contrast, during the rest of the year consumption remains fairly stable during working hours, even though in summer there is a noticeable maximum at sunniest hours as cooling requirements are maximum.

From the annual 900,000kWh, 57% are consumed in the 6 colder months (October to March), although 25% overall just in January and December; and the remaining 43% during the rest of the year.

[5] In case of employing exclusively gas heating, difference would be much less

Table 3.2 Consumption data in kWh

t (h)	January	February	March	April	May	June	July	August	September	October	November	December	Total year
1	74.4	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	66.9	
2	77.0	46.7	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	69.6	
3	78.3	46.5	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	73.4	
4	81.9	50.4	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	74.9	
5	83.0	49.0	41.6	41.6	34.2	29.3	34.2	39.1	41.6	41.6	38.9	75.5	
6	89.7	56.0	133.0	83.3	58.2	36.3	40.9	38.5	58.0	136.9	41.6	78.8	
7	298.4	198.6	117.8	94.6	74.8	65.3	69.2	64.9	73.0	119.3	121.1	279.4	
8	251.0	159.9	157.6	143.0	128.4	138.7	141.8	140.1	138.4	153.9	115.2	233.6	
9	252.6	179.1	141.6	130.1	122.7	134.7	135.0	137.5	129.9	131.5	156.3	230.6	
10	216.8	154.9	132.4	125.2	122.4	137.3	135.0	137.5	129.0	123.7	142.2	197.2	
11	197.8	151.8	130.7	124.7	126.5	142.8	139.8	141.0	131.9	123.9	136.6	182.7	
12	187.0	150.5	131.7	124.7	130.1	145.2	141.1	142.3	130.2	124.8	135.9	175.7	
13	186.9	151.7	127.8	122.2	134.2	152.4	147.8	148.7	131.9	124.5	139.1	175.9	
14	174.9	145.0	121.7	117.9	133.2	149.8	145.5	144.3	127.2	120.3	134.8	164.1	
15	165.6	132.7	117.0	117.7	135.6	151.3	148.9	145.8	125.4	120.6	130.9	154.1	
16	169.4	129.6	118.9	121.1	137.3	160.0	157.3	150.7	127.0	124.4	131.5	155.8	
17	186.8	133.9	109.2	111.6	124.1	142.9	144.5	134.8	114.1	117.4	144.6	176.7	
18	194.3	150.4	83.8	79.8	83.9	95.2	97.8	89.1	79.9	102.4	142.1	177.3	
19	170.9	132.2	98.5	91.5	82.7	91.0	90.9	87.0	87.6	102.8	111.5	151.9	
20	174.3	135.5	91.2	88.0	80.5	83.4	81.4	79.0	72.9	94.0	110.6	153.2	
21	171.0	131.0	95.3	89.9	79.3	81.4	78.2	73.7	71.4	96.0	101.0	148.9	
22	173.7	137.2	41.6	41.6	41.6	41.6	41.6	41.6	41.6	41.6	102.3	150.6	
23	44.1	41.6	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	41.6	41.6	
24	51.1	40.2	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	
Total day	3750.7	2743.3	2225.2	2082.1	2063.4	2212.3	2204.4	2169.2	2044.7	2233.4	2372.5	3427.5	
Total month	116271.0	76812.6	68980.5	62462.1	63965.0	66369.2	68336.9	67244.2	61340.6	69236.5	71176.0	106251.0	**898,445**

3.3 Energy surplus and deficit

In this section the electricity management for the system is provided. Since generation and consumption constantly vary during the day and throughout the year, they never have the same value and therefore either energy surplus or deficit occur. These values are provided in Table 3.3 and are calculated comparing the total power generated in AC with the power consumed by the load, as expressed by (3-2). Positive and negative values represent respectively the energy surplus and deficit.

$$\Delta P(t,m) = P_{DC}(t,m) \cdot \eta_{conv} - P_{cons}(t,m) \tag{3-2}$$

where $\Delta P(t,m)$ is the power surplus/deficit at hour t in a day of the month m, $P_{DC}(t,m)$ is the power generated by the PV modules at hour t in a day of the month m, η_{conv} is the overall DC/AC conversion efficiency and $P_{cons}(t,m)$ is the power consumed by the load at hour t in a day of the month m.

Values in Table 3.1 show a clear imbalance between summer and winter. While in summer days there is a large energy surplus, in winter it is the opposite, there is a remarkable energy deficit during those days. This lack of capacity for supplying energy during winter is an important limitation and one of the main downsides for PV systems.

One could consider to store all the energy surplus from summer and then supplying this electricity in winter when there is deficit. However, to store this amount in batteries would require a little mountain of them, which would not be cost-effective at all. For this project net daily energy deficit during winter will be covered by the grid, while net daily surplus in summer will be used to supply other offices in the university[6].

---

[6] As for many residential applications, this energy could be sold back to the grid at a lower price, but since university has extra consumption it is much more cost-effective to use it at other offices which would have had to buy energy from the grid anyway.

Table 3.3 Net electricity surplus/deficit in kWh

t (h)	January	February	March	April	May	June	July	August	September	October	November	December	Total year
1	-74.4	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-66.9	
2	-77.0	-46.7	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-69.6	
3	-78.3	-46.5	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-73.4	
4	-81.9	-50.4	-38.9	-38.9	-38.9	-9.2	-13.9	-38.9	-38.9	-38.9	-38.9	-74.9	
5	-83.0	-49.0	-41.6	-41.6	5.6	33.7	19.8	-7.8	-41.6	-41.6	-38.9	-75.5	
6	-89.7	-56.0	-133.0	-26.5	34.4	78.5	63.2	29.1	-22.1	-136.9	-41.6	-78.8	
7	-298.4	-198.6	-50.8	44.3	95.8	124.1	110.1	77.0	24.7	-74.9	-121.1	-279.4	
8	-218.5	-100.0	-7.6	83.6	122.3	124.2	113.0	79.5	46.2	-46.6	-65.3	-233.6	
9	-181.7	-51.9	87.5	173.9	199.3	191.9	186.1	150.8	132.9	52.5	-50.5	-166.2	
10	-93.1	28.6	159.2	237.7	254.2	237.2	237.1	203.5	193.8	119.1	23.8	-80.4	
11	-39.6	68.8	201.0	274.5	283.9	261.2	264.4	233.3	227.7	154.3	65.8	-33.2	
12	-16.2	84.0	214.8	286.1	290.3	268.3	274.5	243.3	240.4	163.2	76.9	-15.9	
13	-27.2	72.5	207.1	275.4	273.2	250.8	257.9	226.4	224.1	147.0	58.1	-28.1	
14	-48.8	44.6	175.7	242.0	238.0	214.6	229.3	198.0	189.0	110.6	22.3	-50.1	
15	-92.4	1.4	119.5	182.3	179.3	162.2	175.9	144.2	129.0	49.0	-34.3	-92.1	
16	-146.1	-64.9	38.3	101.3	105.7	88.8	101.6	70.8	48.8	-29.5	-94.1	-141.7	
17	-186.8	-112.1	-37.8	23.5	39.3	34.5	38.7	8.8	-23.2	-87.3	-144.6	-176.7	
18	-194.3	-150.4	-61.1	-25.3	3.6	14.8	9.3	-20.3	-51.9	-102.4	-142.1	-177.3	
19	-170.9	-132.2	-98.5	-67.9	-42.9	-28.1	-36.9	-61.4	-87.6	-102.8	-111.5	-151.9	
20	-174.3	-135.5	-91.2	-88.0	-69.2	-59.1	-61.8	-79.0	-72.9	-94.0	-110.6	-153.2	
21	-171.0	-131.0	-95.3	-89.9	-79.3	-81.4	-78.2	-73.7	-71.4	-96.0	-101.0	-148.9	
22	-173.7	-137.2	-41.6	-41.6	-41.6	-41.6	-41.6	-41.6	-41.6	-41.6	-102.3	-150.6	
23	-44.1	-41.6	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-41.6	-41.6	
24	-51.1	-40.2	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	
Total day	-2812.3	-1283.4	310.8	1310.4	1658.1	1670.7	1653.7	1147.2	810.6	-291.7	-1147.4	-2599.1	
Total month	-87182.3	-35935.5	9636.1	39312.5	51402.4	50119.9	51263.6	35562.2	24318.2	-9043.4	-34421.6	-80571.1	14,461

Storage does play a key role in recovering the daily energy surplus generated during sun hours and then supplying this amount to the office when there is no sun or generation is low.

Table 3.3 can be rearranged as Table 3.4 to illustrate the electricity management that has been described. The most remarkable aspect is that from March to September the system is self-sustainable (the grid is not used) for average generation and consumption values, as the battery bank is able to store and supply enough energy and power to compensate the power deficit and meet the demand. However, due to a permanent electricity deficit no storage is used during January and December, as all power is directly supplied to the office.

It is also interesting to compare the daily values of generation and consumption as well as the energy stored, the energy imported from the grid (deficit) and the energy supplied to other buildings (surplus). This information is illustrated by Figure 3.1.

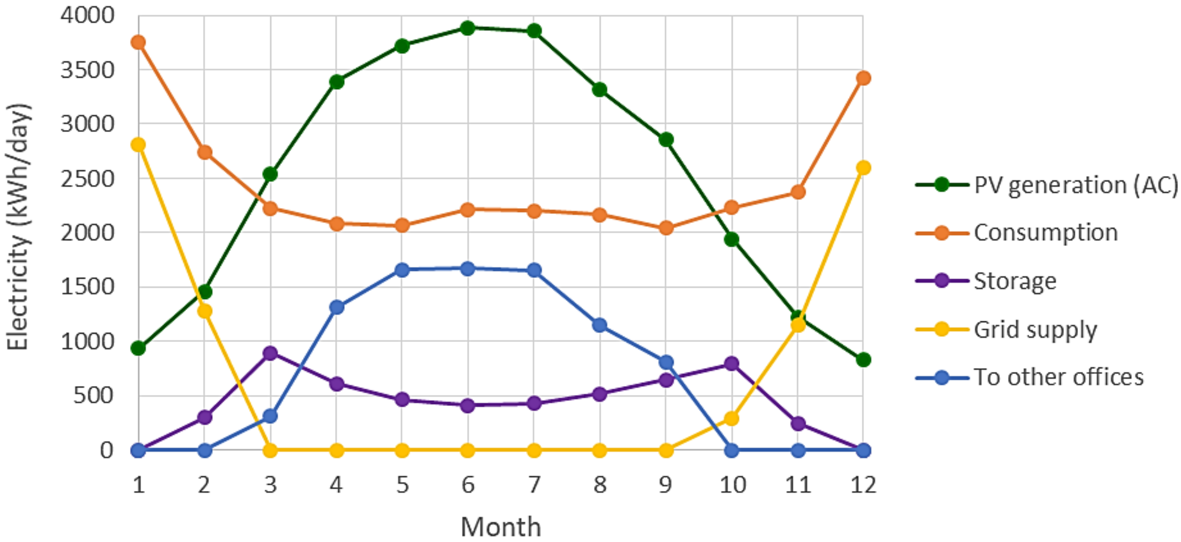

Figure 3.1 Electricity use during the year

As can be observed, during summer the PV farm produces almost double the amount required by the office, and this surplus is profited by other buildings. By contrast, PV generation represents just ¼ of the total energy fed to the load in January and December and the grid must provide the remaining part. Storage is crucial in March and October, as 40% of generation is stored prior to be used.

Table 3.4 Surplus/deficit management, values in kWh.

t (h)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total year
1	-74.4	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-66.9	
2	-77.0	-46.7	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-69.6	
3	-78.3	-46.5	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-73.4	
4	-81.9	-50.4	-38.9	-38.9	-38.9	-9.2	-13.9	-38.9	-38.9	-38.9	-38.9	-74.9	
5	-83.0	-49.0	-41.6	-41.6	5.6	33.7	19.8	-7.8	-41.6	-8.3 | -33.3	-38.9	-75.5	
6	-89.7	-56.0	-133.0	-26.5	34.4	78.5	63.2	29.1	-22.1	-136.9	-41.6	-78.8	
7	-298.4	-198.6	-50.8	44.3	95.8	124.1	110.1	77.0	24.7	-74.9	-121.1	-279.4	
8	-218.5	-100.0	-7.6	83.6	122.3	124.2	113.0	79.5	46.2	-46.6	-65.3	-233.6	
9	-181.7	-51.9	87.5	173.9	199.3	53.6 | 138.3	121.0 | 65.1	150.8	132.9	52.5	-50.5	-166.2	
10	-93.1	28.6	159.2	237.7	9.3 | 244.9	237.2	237.1	181.0 | 22.5	193.8	119.1	23.8	-80.4	
11	-39.6	68.8	201.0	100.2 | 174.3	283.9	261.2	264.4	233.3	227.7	154.3	65.8	-33.2	
12	-16.2	84.0	214.8	286.1	290.3	268.3	274.5	243.3	20.6 | 219.8	163.2	76.9	-15.9	
13	-27.2	72.5	207.1	275.4	273.2	250.8	257.9	226.4	224.1	147.0	58.1	-28.1	
14	-48.8	44.6	22.7 | 153.0	242.0	238.0	214.6	229.3	198.0	189.0	110.6	22.3	-50.1	
15	-92.4	1.4	119.5	182.3	179.3	162.2	175.9	144.2	129.0	49.0	-34.3	-92.1	
16	-146.1	-64.9	38.3	101.3	105.7	88.8	101.6	70.8	48.8	-29.5	-94.1	-141.7	
17	-186.8	-112.1	-37.8	23.5	39.3	34.5	38.7	8.8	-23.2	-87.3	-118.4 | -26.2	-176.7	
18	-194.3	-123.0 | -27.4	-61.1	-25.3	3.6	14.8	9.3	-20.3	-51.9	-102.4	-142.1	-177.3	
19	-170.9	-132.2	-98.5	-67.9	-42.9	-28.1	-36.9	-61.4	-87.6	-102.8	-111.5	-151.9	
20	-174.3	-135.5	-91.2	-88.0	-69.2	-59.1	-61.8	-79.0	-72.9	-94.0	-110.6	-153.2	
21	-171.0	-131.0	-95.3	-89.9	-79.3	-81.4	-78.2	-73.7	-71.4	-96.0	-101.0	-148.9	
22	-173.7	-137.2	-41.6	-41.6	-41.6	-41.6	-41.6	-41.6	-41.6	-41.6	-102.3	-150.6	
23	-44.1	-41.6	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-41.6	-41.6	
24	-51.1	-40.2	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	-38.9	
Grid import/d	-2812.3	-1283.4	-	-	-	-	-	-	-	-291.7	-1147.4	-2599.1	-247,154
To other offi/d	-	-	310.8	1310.4	1658.1	1670.7	1653.7	1147.2	810.6	-	-	-	261,615
Bat charge/d	-	300.0	892.2	614.3	466.7	414.1	427.1	517.4	645.9	795.6	246.8	-	157,067
Bat discharge/d	-	-300.0	-892.2	-614.3	-466.7	-414.1	-427.1	-517.4	-645.9	-795.6	-246.8	-	-157,067

Finally, it is also interesting to compare the annual figures of the energy used by the system. This can be described very visually by means of the Sankey diagram provided as Figure 3.2.

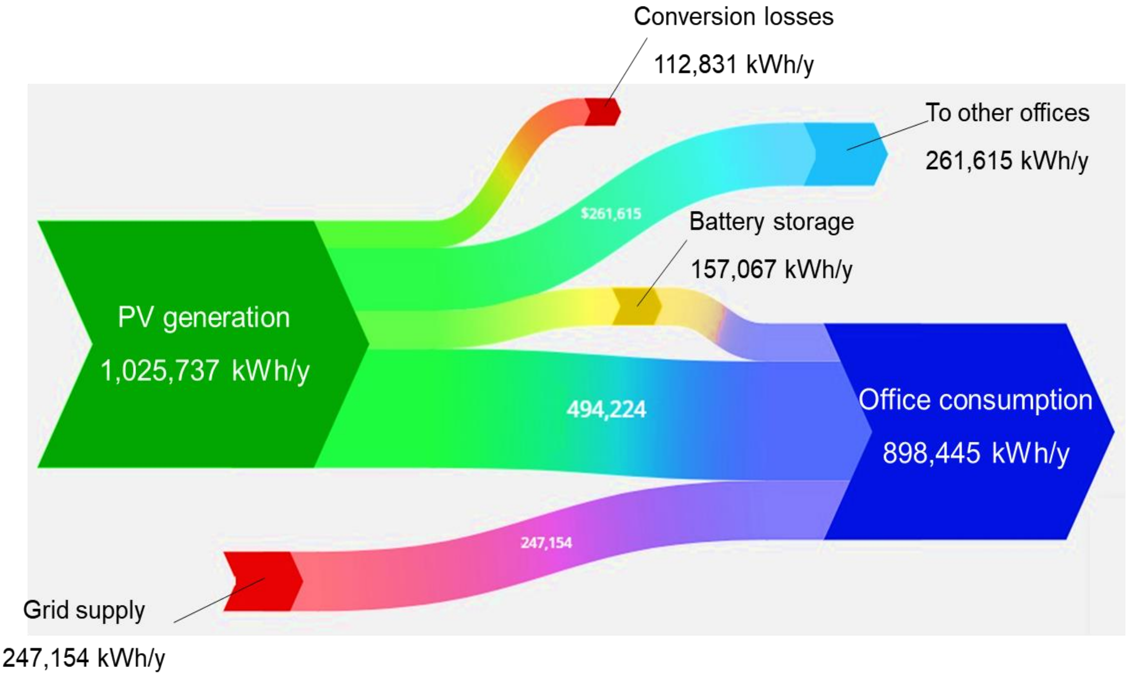

Figure 3.2 Sankey diagram for the annual electricity use

As the figure shows, half of the electricity generated by the PV farm is directly fed to the office. If adding to this the power previously stored in the batteries, results into a 72.49% of the demand covered by means of the PV system.

4. ECONOMIC ANALYSIS

In this section all the costing related to the project is detailed. Comparing these costs to the revenues over the project lifetime, the viability of PV farm can be assessed. Finally, a sensitivity analysis is provided to identify the variables with more impact on the viability of the project.

4.1 Project costs

The main costs for the PV farm are the Capital Expenditure (CAPEX) and Operation and Maintenance (O&M) costs. Each of those is detailed in subsequent sections.

4.1.1 Capital Expenditure

CAPEX involves all costing up front for the project. Detailed costs are given below based on the guidelines of a complete procedure available in [13]. They are calculated from installed facilities in 2015.

All the costs included in the CAPEX have been given in £/W_{DC} for practical reasons and for ease of comparison, as costs are much dependent on the developer, the installer and the size of the project.

CAPEX can be split in four main categories: *1) Total equipment costs, 2) Other direct costs, 3) Indirect costs* and *4) Development costs*. All costs are detailed in Table 4.1.

The total cost per installed Watt is 2.05£/W_{DC}. Up to 67% of this is due to equipment cost, with just PV modules and batteries representing 47% of CAPEX. Total CAPEX can be obtained multiplying the cost per watt by the rated power of the PV farm as (4-1):

$$\boldsymbol{CAPEX} = Cost/W_P \cdot P_{N,PV} = 2.05£/W_P \cdot 710.64kW_P = \mathbf{1,456,812}£ \qquad (4\text{-}1)$$

Table 4.1 Detailed CAPEX for a PV project

Category	Cost per W_{DC}	Description
1) Total Equipment costs		
Modules	0.49£	Ex-factory gate prices
Inverter	0.10£	Ex-factory gate prices
Balance of Systems	0.25£	Ex-factory gate prices (include DC/DC converters)
Batteries	0.47£	Ex-factory gate prices
Sales tax	0.06£	Sales tax on equipment costs
2) Other Direct costs		
Labour costs	0.10£	Direct installation labour, Burden rates
Construction permit & inspection fees	0.03£	
Interconnection	-	Cost included in CP&I fees
3) Indirect costs		
Engineering design	-	Cost included in EPC Overhead
Construction permit administration	-	Cost included in EPC Overhead
EPC Overhead	0.15£	Engineering procurement & construction contractor overhead, inventory, shipping…
EPC SG&A	-	Selling, general & administrative expense Cost included in EPC Overhead
EPC Profit	0.02£	
4) Development costs		
Project Engineering & Management	-	Cost included in developer overhead
Contingencies	0.03£	
Developer Overhead	0.33£	Developer overhead, inventory, shipping…
Developer SG&A	-	Cost included in developer overhead
Developer Profit	0.02£	
TOTAL	**2.05£**	

4.1.2 Operation and maintenance

Besides CAPEX, PV systems also have periodical costs related to their operation and maintenance (O&M), related principally to preventive maintenance of the site and to the replacement of some components. O&M for this project has been estimated following the procedures given by [28, 29].

O&M costs are usually given in £/kW-year and they represent typically about 1% of the CAPEX per year.

Table 4.2 O&M costs for a PV system

Category	Cost per kW-year	Description
General site maintenance	1.20£	Variable depending on size, location and activity.
Wiring/Electrical Inspection	2.10£	Inspection of wires, junctions boxes, AC/DC disconnects, etc.
Panel washing	0.80£	Based on cleaning procedure
Vegetation management	0.90£	Based on site characteristics
Inverter maintenance	4.00£	Cleaning, torqueing, monitoring of internal components, minor equipment repair, etc.
Inverter replacement	6.00£	Included to consider the replacement of the inverter which is the component with a shorter lifecycle
Tracker maintenance	n/a	No tracking is used
Spares	4.00£	Fuses, contacts, disconnect switches, etc.
TOTAL	**19£**	

Hence, yearly O&M costs will be:

$$\boldsymbol{O\&M} = {}^{Cost}/_{kW_P \cdot y} \cdot P_{N,PV} = {}^{19£}/_{kW_P \cdot y} \cdot 710.64 kW_P = \mathbf{13,512£/y} \tag{4-2}$$

4.2 Project revenues

The main revenue of PV plants represents to the saving in the electricity bill due to not purchasing from the grid. However, Feed-in tariff also provides some income.

4.2.1 Saving on electricity bill

Total saving can be calculated as the total amount of energy consumed that has not been purchased from the grid. For this application, all AC power generated is consumed either by the load or by other offices, therefore, for a **grid price** of **14.05p/kWh**, the electricity saving will be:

$$\boldsymbol{E_{saving}} = E_{DC} \cdot \eta_{conv} \cdot price = 1{,}025{,}738 \cdot 0.89 \cdot 0.1405 £/kWh \\ = \mathbf{128{,}263} £/\boldsymbol{y} \tag{4-3}$$

4.2.2 Feed-in tariff

Feed-in Tariff is an environmental policy in the UK [30] for incentivising the installation of renewable energy systems. The government contributes to the investor paying for every kWh generated during 20 years at different rates depending of the type of system. For PV systems between 250-1000kW, the Feed-in Tariff (July 2017) is **1.59p/kWh**. Hence, the yearly revenue will be:

$$\boldsymbol{R_{FIT}} = E_{DC} \cdot \eta_{conv} \cdot FIT = 1{,}025{,}738 \cdot 0.89 \cdot 0.0159 £/kW = \mathbf{14{,}515} £/\boldsymbol{y} \tag{4-4}$$

4.3 Project viability

With all the costs and revenues, the viability of the project can be assessed. To do so, some economic ratios will be employed such as ROI, IRR and Payback and the equivalent cost of electricity will also be calculated for a **project lifecycle of 20 years**.

The Return on Investment (ROI) can be calculated as the final net revenue at the end of the project lifetime divided by the initial investment as:

$$ROI = \frac{\sum_{y=0}^{20} Q_y}{CAPEX} - 1 \tag{4-5}$$

where Q_y is the net cash flow for the year y.

The Internal Rate of Return (IRR) indicates the minimum yearly interest tax which makes the project profitable. Differently than ROI, IRR considers the changing value of money throughout the project lifecycle. It can be calculated iterating for different values of *r* in the formula (4-6):

$$IRR = r \longrightarrow \sum_{y=0}^{20} \frac{Q_y}{(1+r)^y} = 0 \tag{4-6}$$

where Q_y is the net cash flow for the year y and r is the interest tax.

The Payback represents the time required to recover the initial investment. Mathematically can be expressed as (4-7). Since *t* is an integer number, it is necessary to interpolate between the two years where cumulative Q turns to positive.

$$Payback = t \longrightarrow \sum_{y=0}^{t} Q_y = 0 \tag{4-7}$$

where Q_y is the net cash flow for the year y.

Finally, it is also interesting to define the equivalent cost of electricity consumed by the load during the lifetime of the project. This can be calculated as:

$$CoE = \frac{CAPEX/_{20} + E_{grid} \cdot price + O\&M - R_{FIT}}{Consumption} \tag{4-8}$$

where E_{grid} is the yearly amount of electricity supplied by the grid.

All this ratios have been summarised in Table 4.3.

Table 4.3 Economic ratios of the project

ROI (%)	IRR (%)	Payback (years)	CoE (p/kWh)
29.79	2.62	15.4	11.86

As results show, for a lifetime of 20 years project is profitable, and an extra return of 29.79% of the CAPEX will be obtained. The investment will be recovered after 15.4 years. IRR isn't high but is notably greater than the July 2017 UK interest rate, which is currently 0.25% and forecasts predict a value lower than 0.75% by 2020 [31]. Finally, the equivalent cost of consumed electricity during 20 years is 11.86p/kWh, which is lower than the grid price (14.05p/kWh).

4.4 Sensitivity analysis

Realising a sensitivity analysis is crucial to define the performance of the PV system under variations from the expected conditions, providing an indication of the robustness of the system and also identifying the most critical variables and the main risks.

For this project, such an analysis has been focused on IRR and Payback. For several values of different parameters, the new values for IRR and Payback are calculated. The range for each parameter is specified in Table 4.4.

Table 4.4 Values and range for parameters

Parameter	*Initial Value*	*Range (%)*
Grid price	14.05p/kWh	(-20,+20)
Feed-in Tariff	1.59p/kWh	(-50,+50)
Batteries degradation	0.5%/year	(-50,+50)
Battery cost	0.47£/W_p	(-50,+50)
Panel cost	0.49£/W_p	(-50,+50)
Generation	1,025,738kWh/year	(-20,+20)
Consumption	898,445kWh/year	(-20,+20)

Results for IRR are shown in Figure 4.1. There is a clear key parameter affecting the profitability of the system, which is PV generation. For higher values than the forecast, IRR increases drastically, a 70% boost for 10% more generation. On the other hand, a decrease in generation affects dramatically to the IRR, making the project unprofitable for a production fall around 13%. Note that for 20 years, average generation shouldn't be far from the forecast, with a variability around plus-minus 5%.

The second in importance is the grid price. An increase of 10% of this parameter rises IRR by 40%, as for more cost of electricity, the most is the saving in electricity bills if installing a PV system. By contrast, lower prices makes the investment less attractive in economic terms.

Equipment costs such as modules and batteries also affect, as for lower costs the attractiveness of PV is higher. This has been the main reason to the boost in PV technologies in recent years, and tendency is still to continue decreasing.

Finally, degradation of the batteries has no impact as the storage system was dimensioned to not lose the required capacity during the lifetime even for a certain degree of degradation.

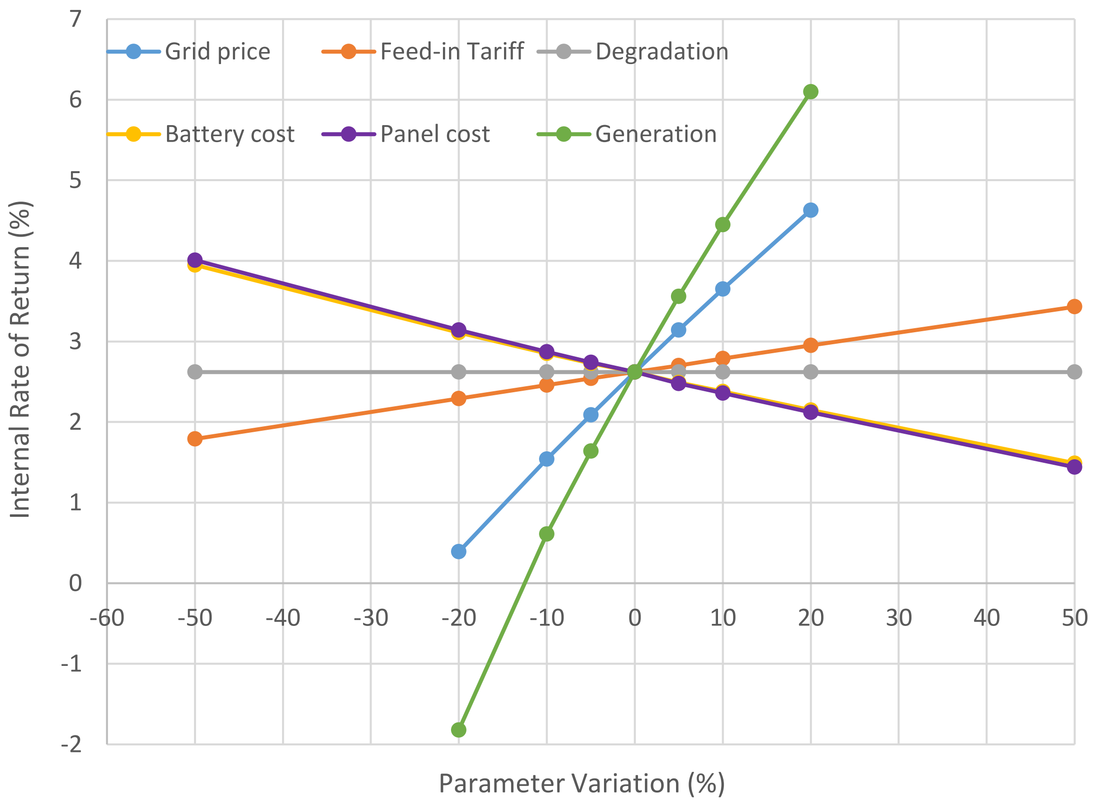

Figure 4.1 Sensitivity analysis for IRR

Similarly than for IRR, it is also interesting to analyse the sensitivity of the Payback, illustrated by Figure 4.2. Logically, variations in parameters contributing to a higher IRR consequently impact on a shorter Payback and vice versa.

Payback can be reduced drastically for higher generation values and extended long in the contrary case, but none of those is likely to occur. For more realistic conditions (-5%,+5%) it can be reduced or extended about 1 and a half year, this is also likely to occur for greater variations in grid price and equipment costs.

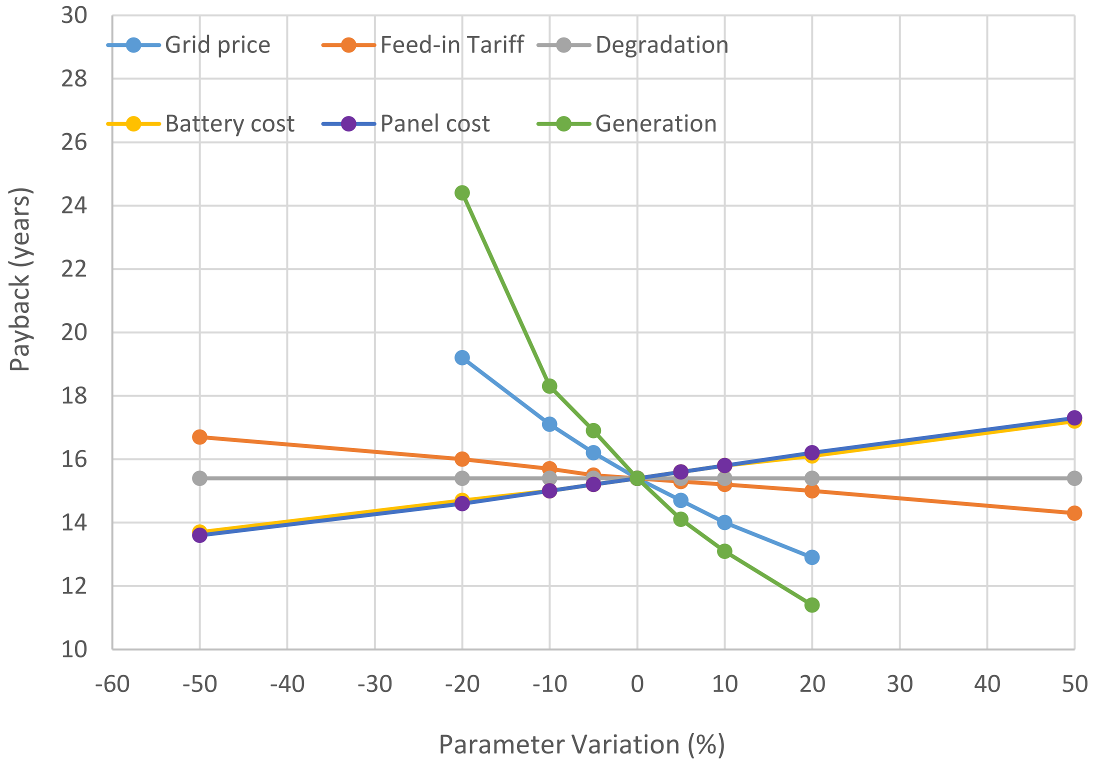

Figure 4.2 Sensitivity analysis for Payback

5. ENVIRONMENTAL ASSESSMENT

This final section assesses the environmental impacts and opportunities of installing a PV farm in Cranfield University.

A solar system has the potential to alter landscape, soil and natural habitats but they also can make a good contribution to the site. The selected location (see Figure 2.13 in section *2.4.3 Farm Layout*) is bounded by the Technology Park in the north, Martell House in the west, Cranfield Road in the south, Stilliters farm in the south-east and Cranfield Airport in the north-east. Its proximity to the airport and the Technology Park will minimize the visual impact of the PV farm, as the area has been already urbanised in its most part.

Since the PV farm would be partially bounded with Stilliters Farm, there is the possibility of using the PV farm site as a grazing area for the animals, in which case panels should be placed at least 1.5m above the ground, but it would be interesting as animals would provide some vegetation maintenance on their own.

However, the biggest contribution of the PV farm itself is the prevention of emitting a huge amount of CO_2 to the atmosphere for generating energy, as a considerable share of grid electricity is produced by burning fossil fuels. Published data of UK electricity system [32] show that in 2016 a total **339TWh of electricity were generated** in the country. Shares of this energy are illustrated by Figure 5.1.

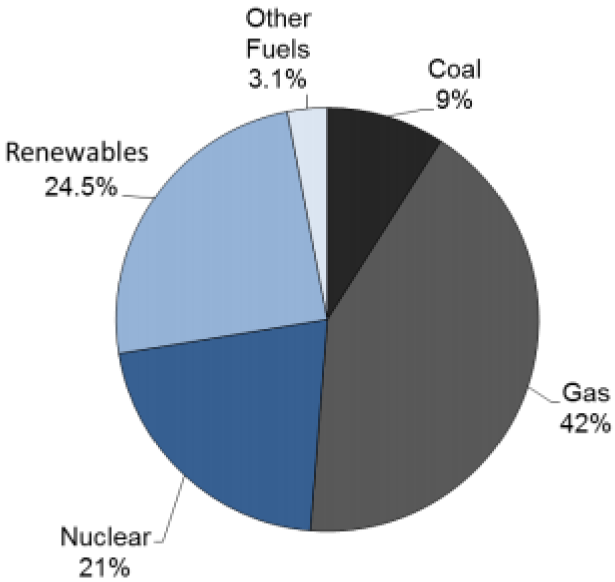

Figure 5.1 Shares of electricity generation in the UK (2016) [32].

As numbers show, more than ½ of the electricity is generated by burning fossil fuels. Average emissions for each technology are also provided in [32], and they are displayed in Table 5.1.

Table 5.1 Average CO2 emissions for each fuel (2016)

Fuel	***Total electricity generated***	***Emissions per GWh of electricity supplied***
Coal	31TWh	925 tonnes CO_2
Gas	143TWh	359 tonnes CO_2
All Fossil Fuels	174TWh	477 tonnes CO_2
All fuels (including Nuclear & Renewables)	339TWh	**254 tonnes CO_2**

Therefore, **for each GWh of electricity** supplied in the UK, **254 tonnes of CO_2 are emitted** to the atmosphere.

Contrarily, electricity generated in a PV farm represents zero emissions, resulting in a huge environmental and social benefit. Since the PV farm supplies:

$$P_{AC} = P_{DC} \cdot \eta_{conv} = 1{,}025{,}738kWh\ /\ year \cdot 0.89 = 912{,}906kWh\ /\ year$$

Then the prevention on CO_2 emission by generating PV electricity instead of buying it from the grid will be:

$$\begin{aligned} \boldsymbol{non\ emitted\ CO_2} &= 912{,}906 kWh/year \cdot 254\ tonnes\ CO_2/GWh \\ &= \mathbf{231.88}\ \boldsymbol{tonnes\ CO_2/year} \end{aligned} \tag{5-1}$$

This huge contribution is definitely a remarkable added value of the project, as this reduction on emissions would have the **same impact as planting 115,939 trees**[7].

[7] A tree can capture 2kg CO_2 a year on average [34].

6. CONCLUSIONS

A technical report about implementing a PV farm in Cranfield University has been developed concerning the main points for the project. The system has been dimensioned and an optimal location has been selected. Technical description of PV generation, control, storage and consumption has been provided in order to give the reader more deep knowledge about PV systems.

The performance of the farm has been estimated based on some empirical data and some strategies for the power management have been proposed with the aim of optimising the operation. The PV system is able to sustain entirely a middle sized office from March to September.

Furthermore, all costs for the PV farm have been detailed using some benchmarking data and an economic analysis for the profitability of the project has been realised. It has been found that the system provides economic benefits by the end of the lifetime. A sensitivity analysis has also been performed to complement the results, checking the robustness of the system and also getting a better understanding of the effects of different parameters on the outcome, finding the generation amount and the grid price as the most relevant.

Finally an environmental assessment has been included to provide some of the effects that PV systems have on their sites, considering some requirements and principally the benefits for the environment of such a system. The highlight is the prevention of emitting a large amount of CO_2 to the atmosphere.

Hopefully this report will be useful as a reference for the procedure of implementing a PV system in the future and also as a starting point for exploring other strategies such as tracking or maximizing the autonomy of the system and for going further in some features as control techniques.

REFERENCES

[1] A. M. Othman, M. M. El-arini, A. Ghitas and A. Fathy, “Realworld maximum power point tracking simulation of PV system based on Fuzzy Logic control,” *NRIAG Journal of Astronomy and Geophysics, Volume 1, Issue 2,* pp. 186-194, 2012.

[2] “Arizona Wind & Sun,” [Online]. Available: https://www.solar-electric.com/learning-center/batteries-and-charging/mppt-solar-charge-controllers.html. [Accessed 23 July 2017].

[3] N. Fuyin, L. Zhengming and S. Lin, “The PV MPPT Control Strategy Based on Generalized Predictive Control,” *The Open Fuels & Energy Science Journal,* vol. 8, pp. 244-251, 2015.

[4] Y. Jiang, J. Qahouq and T. Haskew, “Adaptive step size with adaptive-perturbation-frequency digital MPPT controller for a single-sensor,” *IEEE Trans. Power Electron,* vol. 28, pp. 3195-3205, 2014.

[5] A. Kerr, “To track or not to track,” *Home Power,* vol. April/May, no. 154, 2013.

[6] C. Xie, “The Concord Consortium,” 17 August 2016. [Online]. Available: http://blog.concord.org/choose-solar-trackers-hsat-vsat-or-aadat. [Accessed 26 July 2017].

[7] “Solar Builder,” [Online]. Available: http://solarbuildermag.com/news/array-technologies-to-supply-solar-trackers-for-268-mw-project/. [Accessed 26 July 2017].

[8] “Arc tracker,” [Online]. Available: http://www.arctrackerinc.com/trackers/. [Accessed 26 July 2017].

[9] “Solar Pro,” [Online]. Available: http://solarprofessional.com/articles/products-equipment/racking/pv-trackers?v=disable_pagination&nopaging=1#.WaGDc4g1_IU. [Accessed 26 July 2017].

[10] "Green Tech Media," 28 November 2012. [Online]. Available: https://www.greentechmedia.com/articles/read/solar-balance-of-system-to-track-or-not-to-track-part-i. [Accessed 26 August 2017].

[11] A. Beaudet, "Alte store," 11 June 2015. [Online]. Available: https://www.altestore.com/blog/2015/06/solar-tracking-tips-to-track-or-not-to-track/. [Accessed 26 July 2017].

[12] "NPS Power," [Online]. Available: http://www.npspower.com/symmetric-dual-axis-solar-tracker/. [Accessed 26 July 2017].

[13] R. Fu, D. Chung, T. Lowder, D. Feldman, K. Ardani and R. Margolis, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2016," National Renewable Energy Laboratory, September 2016.

[14] "Solar facts and advice," [Online]. Available: http://www.solar-facts-and-advice.com/support-files/sp_315ewh_en_ltr_p_ds.pdf. [Accessed 27 July 2017].

[15] E. Mehleri, P. Zervas, H. Sarimveis, J. Palyvos and N. Markatos, "Determination of the optimal tilt angle and orientation for solar arrays," *Elsevier,* no. November, 2010.

[16] C. R. Landau, "Optimum Tilt of Solar Panels," 11 November 2015. [Online]. Available: http://www.solarpaneltilt.com/#other. [Accessed 27 July 2017].

[17] Sandia National Laboratories, U. S. Department of Energy, "PVPerformance, Modeling collaborative," [Online]. Available: https://pvpmc.sandia.gov/modeling-steps/1-weather-design-inputs/sun-position/. [Accessed 27 July 2017].

[18] Sandia National Laboratories, U. S. Department of Energy, "PVPerformance, Modeling Collaborative," [Online]. Available: https://pvpmc.sandia.gov/modeling-steps/1-weather-design-inputs/sun-position/simple-models/. [Accessed 2017 July 27].

[19] I. Reda and A. Andreas, "Solar Position Algorithm for Solar Radiation Applications," *Golden, Colorado, National Renewable Energy Laboratory,* 2008.

[20] E. L. Maxwell, “A Quasi-Physical Model for Converting Hourly Global Horizontal to Direct Normal Insolation.,” *Golden, CO, Solar Energy Research,* 1987.

[21] R. Perez, P. Ineichen and e. al., “Dynamic Global-to-Direct Irradiance Converxion Models,” *ASHRAE Transactions 98(1),* 1992.

[22] Joint Resarch Center, European Commision, “PVGIS,” [Online]. [Accessed 27 July 2017].

[23] H. Hottel and B. Woertz, Evaluation of flat-plate solar heat collector., Trans. ASME 64, 91, 1942.

[24] L. P. e. al., “ Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation,” Solar Energy vol. 81, 2007 Solar Energy, pp. 254-267.

[25] U. S. Department of Energy, Office of Energy Efficiency & Renewable Energy (EERE), “Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States,” 2013.

[26] R. Adams, “There's Less To Tesla's Big Australian Battery Deal Than Meets The Eye,” Forbes, 7 July 2017. [Online]. Available: https://www.forbes.com/sites/rodadams/2017/07/07/megahype-over-tesla-battery-capable-of-providing-nameplate-power-for-less-than-80-minutes/#4091358a4919. [Accessed 27 July 2017].

[27] J. P. O'Connor, Off Grid Solar: A handbook for Photovoltaics with Lead-Acid or Lithium-Ion batteries, 2016.

[28] Sandia Laboratories, “Budgeting for solar PV plant operation & maintenance: practices and pricing,” *Electric Power Research Institute,* December 2015.

[29] National Renewable Energy Laboratory, “Distributed Generation Renewable Energy Estimate of Costs,” February 2016. [Online]. Available: https://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html. [Accessed 31 July 2017].

[30] Ofgem, Department of Business, Energy and Industrial Strategy, “Feed-in Tariff (FIT) Rates,” [Online]. Available: https://www.ofgem.gov.uk/environmental-programmes/fit/fit-tariff-rates. [Accessed 31 July 2017].

[31] Trading Economics, “United Kingdom Interest Rate forecast,” [Online]. Available: https://tradingeconomics.com/united-kingdom/interest-rate/forecast. [Accessed 31 July 2017].

[32] Department of Business, Energy and Industrial Strategy, “Digest of UK Energy Statistics (DUKES): Electricity,” July 2017.

[33] “RenSmart,” [Online]. Available: http://www.rensmart.com/Products/SolarPV. [Accessed 27 July 2017].

[34] Forestry Commission, “Mitigation: Planting more trees,” UK Government, [Online]. Available: https://www.forestry.gov.uk/pdf/6_planting_more_trees.pdf/$file/6_planting_more_trees.pdf. [Accessed 1 August 2017].

APPENDICES

Appendix A Technical characteristics of selected equipment

A.1 PV panel comparison

Table A.1 RenSMART Solar Panel Comparison Table [33].

Product	Manufacturer	Width (mm)	Height (mm)	Area (m^2)	Watts/m^2	Efficiency %	Technology	Peak Output (W)	Peak Voltage (V)	Peak Current (A)	Max System Voltage (V)
315 Solar Panel	SunPower	1559	1046	1.63	193.17	19.32	Monocrystalline	315	54.7	5.76	600
230 Solar Panel	SunPower	1559	798	1.24	184.88	18.49	Monocrystalline	230	41	5.61	600
225 Solar Panel	SunPower	1559	798	1.24	180.86	18.09	Monocrystalline	225	41	5.49	600
HIT-N220E01	Sanyo	1580	798	1.26	174.49	17.45	HIT	220	41.6	5.31	1000
HIT-240HDE4	Sanyo	1610	861	1.39	173.13	17.31	HIT	240	35.5	6.77	1000
215 Solar Panel	SunPower	1559	798	1.24	172.82	17.28	Monocrystalline	215	39.8	5.4	600
HIT-N215E01	Sanyo	1580	798	1.26	170.52	17.05	HIT	215	40.9	5.27	1000
HIT-235HDE4	Sanyo	1610	861	1.39	169.53	16.95	HIT	235	35.1	6.7	1000
210 Solar Panel	SunPower	1559	798	1.24	168.8	16.88	Monocrystalline	210	40	5.25	600
STP195S-24-Ad+	Suntech	1580	808	1.28	152.74	15.27	Polycrystalline	195	36.6	5.33	1000
STP190S-24-Ad+	Suntech	1580	808	1.28	148.83	14.88	Polycrystalline	190	36.5	5.2	1000
STP205-18/Ud	Suntech	1482	992	1.47	146.24	14.62	Polycrystalline	215	26.3	7.8	1000
HIT-205DNKHE1	Sanyo	1630	862	1.41	145.9	14.59	HIT	205	41.3	4.97	1000
STP185S-24-Ad	Suntech	1580	808	1.28	144.91	14.49	Monocrystalline	185	36.4	5.09	1000
STP280-24-Vd	Suntech	1956	992	1.94	144.3	14.43	Monocrystalline	280	35.2	7.95	1000
NU-U235F1	Sharp	1640	994	1.63	144.16	14.42	Monocrystaline	235	30	8.4	600
PowerGlaz RG-SMT6(60)P 660235	Romag	1640	994	1.63	144.16	14.42	Polycrystalline	235	30.6	7.7	1000
YL 235 P-29b	Yingli	1650	990	1.63	143.86	14.39	Polycrystalline	235	29.5	7.97	1000
YL 280 P-35b	Yingli	1970	990	1.95	143.57	14.36	Polycrystalline	280	35.5	7.89	1000
YL280-35b	Yingli	1970	990	1.95	143.57	14.36	Polycrystalline	280	35.5	7.89	1000
STP210-18/Ud	Suntech	1482	992	1.47	142.84	14.28	Polycrystalline	210	26.4	7.95	1000
PowerGlaz RG-SMT6(54)P 654210	Romag	1482	994	1.47	142.56	14.26	Polycrystalline	210	27.54	7.6	1000
YL 185 P-23b	Yingli	1310	990	1.3	142.65	14.26	Polycrystalline	185	23.5	7.87	1000
HIT-200DNKHE1	Sanyo	1630	862	1.41	142.34	14.23	HIT	200	40.7	4.92	1000
YL 255 P-32b	Yingli	1810	990	1.79	142.31	14.23	Polycrystalline	255	32.5	7.85	1000
YL 210 P-26b	Yingli	1495	990	1.48	141.89	14.19	Polycrystalline	210	26.6	7.9	1000
STP275-24-Vd	Suntech	1956	992	1.94	141.73	14.17	Monocrystalline	275	35.1	7.84	1000

Product	Manufacturer	Width (mm)	Height (mm)	Area (m^2)	Watts/m^2	Efficiency %	Technology	Peak Output (W)	Peak Voltage (V)	Peak Current (A)	Max System Voltage (V)
KD210GH-2PU	Kyocera	1500	990	1.49	141.41	14.14	Polycrystalline	210	26.6	7.9	1000
PowerGlaz RG-SMT6(48)P 648185	Romag	1318	994	1.31	141.21	14.12	Polycrystalline	185	24.5	7.7	1000
NU-U230F3	Sharp	1640	994	1.63	141.09	14.11	Monocrystaline	230	30	7.67	600
PowerGlaz RG-SMT6(60)P 660230	Romag	1640	994	1.63	141.09	14.11	Polycrystalline	230	30.3	7.6	1000
YL 275 P-35b	Yingli	1970	990	1.95	141	14.1	Polycrystalline	275	35.5	7.75	1000
YL275-35b	Yingli	1970	990	1.95	141	14.1	Polycrystalline	275	35.5	7.75	1000
STP180S-24-Ad	Suntech	1580	808	1.28	141	14.1	Monocrystalline	180	36	5	1000
YL 230 P-29b	Yingli	1650	990	1.63	140.8	14.08	Polycrystalline	230	29.5	7.8	1000
YL230Wp	Yingli	1650	990	1.63	140.8	14.08	Polycrystalline	230	30	7.66	1000
KD185GH-2PU	Kyocera	1338	990	1.32	139.66	13.97	Polycrystalline	185	23.6	7.84	1000
BP4175T	BP Solar	1587	790	1.25	139.58	13.96	Polycrystalline	175	35.4	4.9	1000
YL 250 P-32b	Yingli	1810	990	1.79	139.52	13.95	Polycrystalline	250	32.3	7.74	1000
BP4175N	BP Solar	1593	790	1.26	139.06	13.91	Polycrystalline	175	35.4	4.9	1000
YL 180 P-23b	Yingli	1310	990	1.3	138.79	13.88	Polycrystalline	180	23	7.83	1000
YL180Wp	Yingli	1310	990	1.3	138.79	13.88	Polycrystalline	180	23	7.8	1000
YL 205 P-26b	Yingli	1495	990	1.48	138.51	13.85	Polycrystalline	205	26.5	7.74	1000
YL 270 P-35b	Yingli	1970	990	1.95	138.44	13.84	Polycrystalline	270	35.3	7.65	1000
YL270-35b	Yingli	1970	990	1.95	138.44	13.84	Polycrystalline	270	35.3	7.65	1000
KD95SX-1P	Kyocera	1043	660	0.69	138.01	13.8	Polycrystalline	95	17.9	5.31	750
PowerGlaz RG-SMT6(60)P 660225	Romag	1640	994	1.63	138.02	13.8	Polycrystalline	225	29.9	7.5	1000
YL 225 P-29b	Yingli	1650	990	1.63	137.74	13.77	Polycrystalline	225	29	7.63	1000
ND-224UC1	Sharp	1640	994	1.63	137.41	13.74	Polycrystalline	224	29.3	7.66	600
PowerGlaz RG-SMT6(48)P 648180	Romag	1318	994	1.31	137.39	13.74	Polycrystalline	180	23.9	7.6	1000
PV-TD190MF5	Mitsubishi	1658	834	1.38	137.41	13.74	Polycrystalline	190	24.7	7.71	1000
PV-AD190MF5	Mitsubishi	1658	834	1.38	137.41	13.74	Polycrystalline	190	24.7	7.71	1000
YL 245 P-32b	Yingli	1810	990	1.79	136.73	13.67	Polycrystalline	245	32.2	7.61	1000
STP225-20-Wd	Suntech	1665	991	1.65	136.36	13.64	Polycrystalline	225	29.6	7.61	1000
KD70SX-1P	Kyocera	778	660	0.51	136.32	13.63	Polycrystalline	70	17.9	3.92	750
YL 265 P-35b	Yingli	1970	990	1.95	135.88	13.59	Polycrystalline	265	35.3	7.5	1000
YL265P-35b	Yingli	1970	990	1.95	135.88	13.59	Polycrystalline	265	35.3	7.5	1000
PowerGlaz RG-SMT6(54)P 654200	Romag	1482	994	1.47	135.77	13.58	Polycrystalline	200	26.91	7.5	1000
BP3170N	BP Solar	1593	790	1.26	135.08	13.51	Polycrystalline	170	35.5	4.8	1000

Product	Manufacturer	Width (mm)	Height (mm)	Area (m^2)	Watts/m^2	Efficiency %	Technology	Peak Output (W)	Peak Voltage (V)	Peak Current (A)	Max System Voltage (V)
YL 200 P-26b	Yingli	1495	990	1.48	135.13	13.51	Polycrystalline	200	26.3	7.6	1000
PowerGlaz RG-SMT6(60)P 660220	Romag	1640	994	1.63	134.96	13.5	Polycrystalline	220	29.4	7.5	1000
YL 175 P-23b	Yingli	1310	990	1.3	134.94	13.49	Polycrystalline	175	23	7.61	1000
YL175Wp	Yingli	1310	990	1.3	134.94	13.49	Polycrystalline	175	23.5	7.5	1000
KD135GH-2PU	Kyocera	1500	668	1	134.73	13.47	Polycrystalline	135	17.7	7.63	1000
KD135SX-1PU	Kyocera	1500	668	1	134.73	13.47	Polycrystalline	135	17.7	7.63	750
YL 220 P-29b	Yingli	1650	990	1.63	134.68	13.47	Polycrystalline	220	29	7.59	1000
SCHOTT POLY 225	Schott	1685	993	1.67	134.47	13.45	Polycrystalline	225	29.8	7.55	600
PV-MF170EB4	Mitsubishi	1580	800	1.26	134.49	13.45	Polycrystalline	170	24.6	6.93	780
YL 240 P-32b	Yingli	1810	990	1.79	133.94	13.39	Polycrystalline	240	32.2	7.45	1000
PV-TD185MF5	Mitsubishi	1658	834	1.38	133.79	13.38	Polycrystalline	185	24.4	7.58	1000
PV-MF185TD4	Mitsubishi	1658	834	1.38	133.79	13.38	Polycrystalline	185	24.4	7.58	780
PV-AD185MF5	Mitsubishi	1658	834	1.38	133.79	13.38	Polycrystalline	185	24.4	7.58	1000
ND-198UC1	Sharp	1491	994	1.48	133.6	13.36	Polycrystalline	198	26.3	7.52	600
PowerGlaz RG-SMT6(48)P 648175	Romag	1318	994	1.31	133.58	13.36	Polycrystalline	175	23.5	7.5	1000
ND-176UC1	Sharp	1328	994	1.32	133.33	13.33	Polycrystalline	176	23.42	7.52	600
YL 260 P-35b	Yingli	1970	990	1.95	133.31	13.33	Polycrystalline	260	35	7.43	1000
YL260P-35b	Yingli	1970	990	1.95	133.31	13.33	Polycrystalline	260	35	7.43	1000
STP220-20-Wd	Suntech	1665	991	1.65	133.33	13.33	Polycrystalline	220	29.5	7.46	1000
PowerGlaz RG-SMT6(54)P 654195	Romag	1482	994	1.47	132.37	13.24	Polycrystalline	195	26.35	7.4	1000
YL 195 P-26b	Yingli	1495	990	1.48	131.75	13.18	Polycrystalline	195	26	7.5	1000
YL 215 P-29b	Yingli	1650	990	1.63	131.62	13.16	Polycrystalline	215	29	7.41	1000
SCHOTT POLY 220	Schott	1685	993	1.67	131.48	13.15	Polycrystalline	220	29.7	7.41	600
YL 170 P-23b	Yingli	1310	990	1.3	131.08	13.11	Polycrystalline	170	23	7.39	1000
YL 235 P-32b	Yingli	1810	990	1.79	131.15	13.11	Polycrystalline	235	32	7.34	1000
ND-130UJF	Sharp	1499	662	0.99	131	13.1	Polycrystalline	130	17.4	7.5	600
PowerGlaz RG-SMT5(36)M	Romag	1197	530	0.63	130.83	13.08	Monocrystalline	83	18.1	4.6	1000
NE-170UC1	Sharp	1575	826	1.3	130.67	13.07	Polycrystalline	170	34.8	4.9	600
PV-MF165EB4	Mitsubishi	1580	800	1.26	130.54	13.05	Polycrystalline	165	24.2	7.36	780
PV-MF120EC4	Mitsubishi	1425	646	0.92	130.36	13.04	Polycrystalline	120	17.6	6.84	780
PV-TD180MF5	Mitsubishi	1658	834	1.38	130.17	13.02	Polycrystalline	180	24.2	7.45	1000
PV-MF180TD4	Mitsubishi	1658	834	1.38	130.17	13.02	Polycrystalline	180	24.2	7.45	780

Product	Manufacturer	Width (mm)	Height (mm)	Area (m²)	Watts/m²	Efficiency %	Technology	Peak Output (W)	Peak Voltage (V)	Peak Current (A)	Max System Voltage (V)
PV-AD180MF5	Mitsubishi	1658	834	1.38	130.17	13.02	Polycrystalline	180	24.2	7.45	1000
PowerGlaz RG-SMT6(48)P 648170	Romag	1318	994	1.31	129.76	12.98	Polycrystalline	170	23.1	7.4	1000
SCHOTT POLY 217	Schott	1685	993	1.67	129.69	12.97	Polycrystalline	217	29.6	7.33	600
PV-MF130EA4	Mitsubishi	1248	803	1	129.72	12.97	Polycrystalline	130	19.2	6.79	600
PowerGlaz RG-SMT6(54)P 654190	Romag	1482	994	1.47	128.98	12.9	Polycrystalline	190	26.03	7.3	1000
PV-TE130MF5N	Mitsubishi	1495	674	1.01	129.02	12.9	Polycrystalline	130	17.4	7.47	1000
PV-MF130TE4N	Mitsubishi	1495	674	1.01	129.02	12.9	Polycrystalline	130	17.4	7.47	780
PV-AE130MF5N	Mitsubishi	1495	674	1.01	129.02	12.9	Polycrystalline	130	17.4	8.05	1000
PowerGlaz RG-SMT6(60)P 660210	Romag	1640	994	1.63	128.82	12.88	Polycrystalline	210	28.4	7.4	1000
YL 210 P-29b	Yingli	1650	990	1.63	128.56	12.86	Polycrystalline	210	28.5	7.37	1000
YL210Wp	Yingli	1650	990	1.63	128.56	12.86	Polycrystalline	210	29.5	7.2	1000
YL 190 P-26b	Yingli	1495	990	1.48	128.37	12.84	Polycrystalline	190	25.8	7.36	1000
YL 165 P-23b	Yingli	1310	990	1.3	127.23	12.72	Polycrystalline	165	23	7.17	1000
BP3160N	BP Solar	1593	790	1.26	127.14	12.71	Polycrystalline	160	35.1	4.55	1000
NE-165UC1	Sharp	1575	826	1.3	126.83	12.68	Polycrystalline	165	34.6	4.77	600
PV-TD175MF5	Mitsubishi	1658	834	1.38	126.56	12.66	Polycrystalline	175	23.9	7.32	1000
PV-MF175TD4	Mitsubishi	1658	834	1.38	126.56	12.66	Polycrystalline	175	23.9	7.32	780
PV-AD175MF5	Mitsubishi	1658	834	1.38	126.56	12.66	Polycrystalline	175	23.9	7.32	1000
PV-MF160EB4	Mitsubishi	1580	800	1.26	126.58	12.66	Polycrystalline	160	23.8	6.72	780
PowerGlaz RG-SMT6(48)P 648165	Romag	1318	994	1.31	125.95	12.59	Polycrystalline	165	22.5	7.4	1000
PowerGlaz RG-SMT6(60)P 660205	Romag	1640	994	1.63	125.75	12.58	Polycrystalline	205	27.9	7.3	1000
SCHOTT POLY 210	Schott	1685	993	1.67	125.51	12.55	Polycrystalline	210	29.3	7.16	600
PV-MF125EA4	Mitsubishi	1248	803	1	124.73	12.47	Polycrystalline	125	18.8	6.63	600
NE-80EJEA	Sharp	1200	537	0.64	124.15	12.41	Polycrystalline	80	21.6	4.63	600
PV-TE125MF5N	Mitsubishi	1495	674	1.01	124.05	12.41	Polycrystalline	125	17.3	7.23	1000
PV-MF125TE4N	Mitsubishi	1495	674	1.01	124.05	12.41	Polycrystalline	125	17.3	7.23	780
PV-AE125MF5N	Mitsubishi	1495	674	1.01	124.05	12.41	Polycrystalline	125	17.3	7.9	1000
ND-123UJF	Sharp	1499	662	0.99	123.95	12.39	Polycrystalline	123	17.2	7.15	600
BP380J	BP Solar	1209	537	0.65	123.22	12.32	Polycrystalline	80	17.6	4.6	600
PV-MF170TD4	Mitsubishi	1658	834	1.38	122.94	12.29	Polycrystalline	170	23.7	7.19	780
PowerGlaz RG-SMT6(48)P 648160	Romag	1318	994	1.31	122.13	12.21	Polycrystalline	160	21.9	7.31	1000
KC32T	Kyocera	517	512	0.26	120.89	12.09	Polycrystalline	32	17.4	1.84	50

Product	Manufacturer	Width (mm)	Height (mm)	Area (m^2)	Watts/m^2	Efficiency %	Technology	Peak Output (W)	Peak Voltage (V)	Peak Current (A)	Max System Voltage (V)
PV-MF110EC4	Mitsubishi	1425	646	0.92	119.49	11.95	Polycrystalline	110	17.1	6.43	780
PV-TE120MF5N	Mitsubishi	1495	674	1.01	119.09	11.91	Polycrystalline	120	17.2	6.99	1000
PV-MF120TE4N	Mitsubishi	1495	674	1.01	119.09	11.91	Polycrystalline	120	17.2	6.99	780
PV-AE120MF5N	Mitsubishi	1495	674	1.01	119.09	11.91	Polycrystalline	120	17.2	7.75	1000
PV-TE115MF5N	Mitsubishi	1495	674	1.01	114.13	11.41	Polycrystalline	115	17.1	6.75	1000
PV-MF115TE4N	Mitsubishi	1495	674	1.01	114.13	11.41	Polycrystalline	115	17.1	6.75	780
PV-AE115MF5N	Mitsubishi	1495	674	1.01	114.13	11.41	Polycrystalline	115	17.1	7.6	1000
KC21T	Kyocera	367	512	0.19	111.76	11.18	Polycrystalline	21	17.4	1.12	50
BP350J	BP Solar	839	537	0.45	110.98	11.1	Polycrystalline	50	17.5	2.9	600
KC16T	Kyocera	517	280	0.14	110.53	11.05	Polycrystalline	16	17.4	0.93	50
C21e	SolarCentury	1220	420	0.51	101.48	10.15	Monocrystalline	52	9.8	5.3	600
SX-330U	BP Solar	595	502	0.3	100.44	10.04	Polycrystalline	30	16.8	1.78	50
NA-V142H5	Sharp	1409	1009	1.42	99.88	9.99	Thin Film	142	188	0.72	1000
KD50SE-1P	Kyocera	706	744	0.53	95.19	9.52	Polycrystalline	50	17.9	2.8	750
NA-V135H5	Sharp	1409	1009	1.42	94.96	9.5	Thin Film	135	192	0.74	1000
SX-320U	BP Solar	502	425	0.21	93.74	9.37	Polycrystalline	20	16.8	1.19	50
NA-V128H5	Sharp	1409	1009	1.42	90.03	9	Thin Film	128	186	0.688	1000
SX-310J	BP Solar	425	273	0.12	86.19	8.62	Polycrystalline	10	16.8	0.59	50
NA-V121H5	Sharp	1409	1009	1.42	85.11	8.51	Thin Film	121	180	0.673	1000
Imerys Roof Tile	Imerys	1377	475	0.65	84.09	8.41	Polycrystalline	55	0	0	0
NA-V115H5	Sharp	1409	1009	1.42	80.89	8.09	Thin Film	115	174	0.661	1000
SX-305M	BP Solar	269	251	0.07	74.05	7.41	Polycrystalline	5	16.5	0.27	50
STP380Ts-DA	Suntech	2600	2200	5.72	66.43	6.64	Thinfilm	380	148.4	2.56	1000
STP370Ts-DA	Suntech	2600	2200	5.72	64.69	6.47	Thinfilm	370	147.4	2.51	1000
STP185Ts-BA	Suntech	2200	1300	2.86	64.69	6.47	Thinfilm	185	147.4	1.26	1000
STP185Ts-CA	Suntech	2600	1100	2.86	64.69	6.47	Thinfilm	185	73.7	2.51	1000
STP090Ts-AA	Suntech	1300	1100	1.43	62.94	6.29	Thinfilm	90	73.2	1.23	1000
STP360Ts-DA	Suntech	2600	2200	5.72	62.94	6.29	Thinfilm	360	146.3	2.46	1000
STP180s-BA	Suntech	2200	1300	2.86	62.94	6.29	Thinfilm	180	146.4	1.23	1000
STP180Ts-CA	Suntech	2600	1100	2.86	62.94	6.29	Thinfilm	180	73.2	2.46	1000
STP090Ts-AC	Suntech	1309	1109	1.45	62	6.2	Thinfilm	90	73.2	1.23	1000
STP350Ts-DA	Suntech	2600	2200	5.72	61.19	6.12	Thinfilm	350	145.2	2.41	1000

Product	Manufacturer	Width (mm)	Height (mm)	Area (m²)	Watts/m²	Efficiency %	Technology	Peak Output (W)	Peak Voltage (V)	Peak Current (A)	Max System Voltage (V)
STP175s-BA	Suntech	2200	1300	2.86	61.19	6.12	Thinfilm	175	145.2	1.21	1000
STP175Ts-CA	Suntech	2600	1100	2.86	61.19	6.12	Thinfilm	175	72.6	2.41	1000
STP086Ts-AA	Suntech	1300	1100	1.43	60.14	6.01	Thinfilm	86	72.3	1.19	1000
STP170s-BA	Suntech	2200	1300	2.86	59.44	5.94	Thinfilm	170	144.1	1.18	1000
STP170Ts-CA	Suntech	2600	1100	2.86	59.44	5.94	Thinfilm	170	72	2.36	1000
STP086Ts-AC	Suntech	1309	1109	1.45	59.24	5.92	Thinfilm	86	72.3	1.19	1000
STP082s-AA	Suntech	1300	1100	1.43	57.34	5.73	Thinfilm	82	71.3	1.15	1000
STP082Ts-AC	Suntech	1309	1109	1.45	56.49	5.65	Thinfilm	82	71.3	1.15	1000

A.2 Tesla Powerpack 2.0 Datasheet

Overall System Specs

AC Voltage	380 to 480V, 3 phases
Communications	Modbus TCP/IP; DNP3
Power	50kW (AC) per Powerpack
Scalable Inverter Power	from 50kVA to 625kVA (at 480V)
Depth of Discharge	100%
Dimensions	**Powerpack** Length: 1,308 mm (51.5") Width: 822 mm (32.4") Height: 2,185 mm (86") Weight: 1622 kg (3575 lbs) **Industrial Inverter** Length: 1,014 mm (39.9") Width: 1254 mm (49.4") Height: 2192 mm (86.3") Weight: 1200 kg (2650 lbs)
Energy Capacity	210 kWh (AC) per Powerpack
Operating Temperature	-22°F to 122°F / -30°C to 50°C
Enclosures	Pods: IP67 Powerpack: IP35/NEMA 3R Inverter: IP66/NEMA 4
System Efficiency (AC) *	88% round-trip (2 hour system) 89% round-trip (4 hour system)
Certifications	Nationally accredited certifications to international safety, EMC, utility and environmental legislation.

* Net Energy delivered at 25°C (77°F) ambient temperature including thermal control

Appendix B Extra content

B.1 Matlab script for calculating solar angles and AOI

```
% Sun_array_position

Longsm=0;
Longlocal=-0.63;     % in degrees
Latitude=52.07;
Ot=42.6*pi/180;      % tilt angle of the array in rad
Oa_array=pi;         % azimuth angle of the array in rad

for n=1:1:365

    Od=23.45*pi/180*sin(2*pi*(284+n)/365);  % Declination of sun

    if 1<=n && n<=106
        Eqt=-14.2*sin(pi*(n+7)/111);

    elseif 107<=n && n<=166
        Eqt=4.0*sin(pi*(n-106)/59);

    elseif 167<=n && n<=246
        Eqt=-6.5*sin(pi*(n-166)/80);

    elseif 147<=n && n<=365
        Eqt=16.4*sin(pi*(n-247)/113);

    end

    for Tlocal=1:1:24

        Tsolar=Tlocal+Eqt/60+(Longsm-Longlocal)/15 ;     % hour angle
changes by 15 degrees each hour (360°/24)
        Ohr=pi*(12-Tsolar)/12 ;       % hour angle in rad

cosOz=sin(pi*Latitude/180)*sin(Od)+cos(pi*Latitude/180)*cos(Od)*cos(Oh
r);
        Oz(n,Tlocal)=acos(cosOz);     % sun zenith angle in rad

        cosOa=(sin(Od)*cos(pi*Latitude/180)-
cos(Od)*sin(pi*Latitude/180)*cos(Ohr))/sin(Oz(n,Tlocal));

        if Ohr<=0
            Oa(n,Tlocal)=acos(cosOa);   % azimuth angle in rad

        elseif Ohr>0
            Oa(n,Tlocal)=2*pi-acos(cosOa);

        end
```

```
cosAOI=cos(Oz(n,Tlocal))*cos(Ot)+sin(Oz(n,Tlocal))*sin(Ot)*cos((Oa(n,T
local))-Oa_array);
        AOI(n,Tlocal)=acos(cosAOI);     % angle of incidence between
        the sun beam & the PV array

        if AOI(n,Tlocal)>pi/2

            AOI(n,Tlocal)=pi/2 ;        % AOI greater than 90° don't
reach the upper plane of the array
                                        % & are set at 90° to avoid
                                        % negative beam irradiances in
                                        % further calculations


        end

    end

    plot (n,Od,'.')
    hold on

end

xlabel('n (day of year)')
ylabel('Od (rad)')
```